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ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD

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TECHNICAL PROCEEDINGS
AC/243-TP/2
Volume 1

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Proceedings from the 30th DRG Seminar on The Defence of Small Ships against Missile Attacks

Defence Research Group

Actes du 30ième Séminaire sur la défense de petits navires contre les attaques de missiles

Groupe sur la Recherche pour la Défense

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14. Abstract:

Proceedings from the DRG 30th Seminar on the Defence of Small Ships Against Missile Attacks. Sessions were on Description of the Threat, Sensors and Sensor Integration, Weapons Coordination and C2, Hard-Kill Weapons Performance, Soft-Kill Weapons Performance, Signature Reduction, and Methodologies for Cost Effectiveness.

CONSEIL DE L'ATLANTIQUE NORD
NORTH ATLANTIC COUNCIL

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TECHNICAL PROCEEDINGS
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Volume 1

DEFENCE RESEARCH GROUP

Proceedings from the 30th DRG Seminar on The Defence of Small Ships Against Missile Attacks 12-14 September 1990, Ottawa, Canada

These are the proceedings from the 30th DRG Seminar on The Defence of Small Ships Against Missile Attacks, held 12-14 September 1990 in Ottawa, Canada. Mr. P. Yansouni was director for the Seminar. The proceedings have been issued in three volumes to enhance circulation: Volume 1 NATO UNCLASSIFIED, Volume 2 NATO RESTRICTED and CONFIDENTIAL, and Volume 3 NATO SECRET papers.

(Signed) Mr. V. LEMCHE
Defence Research Section

NATO,
1110 Brussels.

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EXECUTIVE SUMMARY

1. The response to the Seminar announcement was generally very good with 59 papers submitted, of which approximately one third found their way into the formal sessions and another third into the poster session. Papers selected for the poster session were those of a more specialized nature. Another third of the papers were judged to be of less direct relevance to the topic of the seminar and were not included in the programme. The distribution of papers by subject is shown on the enclosed figure.

2. The bulk of the presentations covered three important areas:

- sensor integration
- coordination of weapons and command and control
- the performance of soft and hard kill weapons.

Some attention was also given to the reduction of platform signatures and to techniques for optimizing system design. Following are some remarks on the coverage of these topics.

(a) A very good case was made for the integration of radar and infrared sensors as well as assessments of the future performance of these sensors against the threat described in the first session. However, passive RF sensors such as Radar ESM, received only cursory treatment, although in many cases, ESM will provide the earliest detection of an antiship missile. This is particularly true in the case of long range supersonic missiles and those launched on bearing information only. Integration of ESM with radar and IR sensors has implications with respect to ESM performance in terms of bearing accuracy, sensitivity and robustness in the presence of interfering Anti-Air Warfare radars, which were not addressed, although current ESM technology can provide the required performance.

(b) Several papers addressed the deployment of soft kill weapons, hard kill weapons and the coordinated use of both under control of the command and control system. Unfortunately, soft kill deployment exclusively addressed RF guided missiles. The problems posed by seeker systems operating in more than one region of the electromagnetic spectrum, combining active and passive guidance (for example, RF-IR or X and Ku band combinations) was not considered in the presentations.

(c) Several architectures for integration and control of the sensors and weapons were described. However, the technology necessary to implement such systems received little attention. Issues such as a centralized processing architecture versus a distributed one, the associated requirements for data transfer, and the software engineering approaches most appropriate to the development of such systems are examples of topics not addressed.

(d) The area of hard and soft kill weapons performance received sufficient coverage, although some discussion on the applicability of directed energy weapons and the means of deploying decoys would have been welcomed.

3. Despite some holes in the coverage, the presentations offered an excellent overview of a vast and very complex topic, requiring contributions from many technical areas. This overview was complemented by the poster session which provided an opportunity for specialists to interact. In general, the content of the papers and quality of the deliveries were very good and the relatively large audience participated eagerly during time allotted to questions.

4. The success of this seminar is due for the most part to the contributions of the many authors and to the session chairpersons who managed and stirred the discussions. To all of them, I wish to express my most sincere appreciation.

Mr. P. Yansouni
Seminar Director

DISTRIBUTION OF PAPERS BY TOPIC

1. Sensors 10
2. Integration of Sensors 7
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4. Command and Control 5
5. Networking Technology 2
6. Software Technology 2
7. Hard Kill Weapons Performance 9
8. Soft Kill Weapons Performance 6
9. Signature Reduction 3
10. Characteristics of the Threat 2
11. Operational Deployment 1
12. Cost Effectiveness Methods 6

TOTAL: 59 papers: 21 in Main Session
21 in Poster Session
17 not accepted

IIIIIIIIII Paper in Main Session

////////// Paper in Poster Session

---------- Paper not accepted

NOTE DE SYNTHESE

1. L'annonce du séminaire a reçu un accueil très positif; sur les 59 contributions reçues, un tiers environ a été présenté dans le cadre des séances formelles, un autre tiers lors de la séance de démonstration. Les exposés retenus pour la séance de démonstration étaient de nature plus scientifique. Le dernier tiers de contributions reçues, qui est apparu moins directement lié au thème du séminaire, n'a pas été inclus au programme. Le schéma joint au présent document illustre la répartition des exposés par thème.

2. Trois grands thèmes dominaient l'ensemble des communications :

- l'intégration des capteurs
- la coordination entre les armes et le système de commandement et de contrôle
- les performances des armes de destruction et de neutralisation.

Les thèmes de la réduction des signatures des plates-formes et des techniques visant à optimiser la conception des systèmes ont également été évoqués. On trouvera ci-dessous quelques remarques sur la façon dont ces trois aspects ont été traités.

(a) Les arguments en faveur de l'intégration des systèmes de détection radar et infrarouges, ainsi que des évaluations de leurs performances futures face à la menace décrite lors de la première séance de travail, ont été présentés de façon très convaincante. Toutefois, les systèmes de capteurs RF passifs, tels que les MSE radar, ont été traités de manière plus superficielle, bien que dans de nombreux cas ce soient les MSE qui offrent la possibilité la plus précoce de détection, par exemple d'un missile antinavire. Cela est particulièrement vrai pour les missiles supersoniques à longue portée ainsi que pour les missiles lancés sur la base des seules informations de gisement. L'intégration des MSE aux systèmes de détection radar et infrarouges a des incidences

sur les performances des MSE en ce qui concerne leur précision en azimut, leur sensibilité et leur robustesse en présence de radars de guerre antiaérienne, qui n'ont pas été abordés lors du séminaire, bien que les techniques actuelles des MSE puisse offrir les performances requises.

(b) Plusieurs exposés ont porté sur le déploiement des armes de destruction et de neutralisation, ainsi que sur leur utilisation coordonnée par le système de commandement et de contrôle. On peut regretter que le déploiement des armes de neutralisation n'ait été envisagé que sous l'angle des missiles à guidage RF. En outre, les problèmes posés par les systèmes à autodirecteur opérant dans plus d'une région du spectre électromagnétique et combinant guidage actif et passif (par exemple, des combinaisons hyperfréquences/infrarouge ou bandes X et Ku) n'ont pas été abordés dans les exposés.

(c) Plusieurs architectures destinées à l'intégration et au contrôle des capteurs et des armes ont été décrites. Toutefois, la technologie nécessaire pour la mise en oeuvre de ces systèmes n'a pas été que peu évoquée. Certains aspects n'ont pas été abordés, tels que l'intérêt relatif d'une architecture de traitement centralisée par rapport à une architecture répartie, les besoins associés en matière de transfert de données, et les approches du génie logiciel convenant le mieux au développement de ces systèmes.

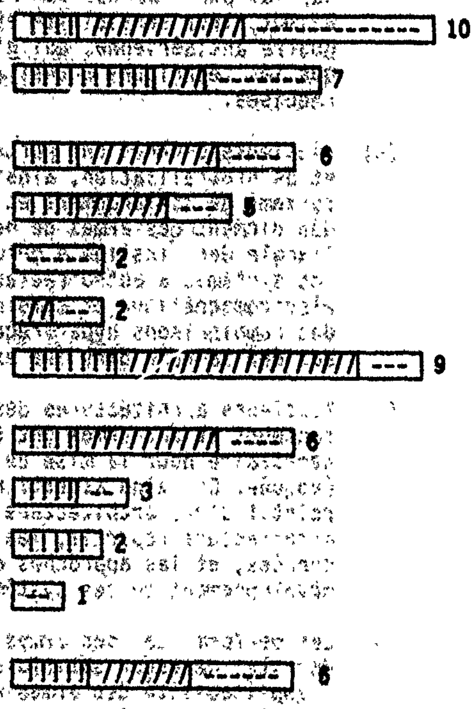
(d) Les performances des armes de destruction et de neutralisation ont été décrites de façon satisfaisante; quelques développements sur l'applicabilité des armes à énergie dirigée et sur les méthodes de déploiement des leurres auraient toutefois été appréciés.

3. Malgré certaines lacunes, les exposés ont fourni un excellent aperçu de ce thème vaste et très complexe, faisant appel à des contributions venant de différents domaines techniques. Ce tour d'horizon a été complété par une séance de démonstration, qui a permis aux spécialistes de dialoguer. Dans l'ensemble, le contenu des exposés et la qualité des présentations ont été d'un très bon niveau. Les participants, relativement nombreux, sont intervenus de façon très active pendant le temps alloué aux discussions.

4. La réussite de ce séminaire est due en majeure partie aux contributions des nombreux auteurs et à la participation des présidents de séance qui ont organisé et animé les débats. A tous, j'adresse mes plus sincères remerciements pour le travail accompli.

(Signé) M. P. YANSOUNI
Directeur du séminaire

REPARTITION DES EXPOSES PAR THEME



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TOTAL : 59 exposés : 21 présentés lors de la séance principale
21 présentés lors de la séance de démonstration
17 non retenus

exposé présenté lors de la séance principale

exposé présenté lors de la séance de démonstration

exposé non retenu

OPENING ADDRESS

BY

DR A J GRANT, CHAIRMAN OF THE DEFENCE RESEARCH GROUP

Dr Schofield, Admiral Anderson, ladies and gentlemen.

As Chairman of the Defence Research Group, I am pleased to have the opportunity to address you at the opening of this Seminar on "The Defence of Small Ships against Missile Attack". On behalf of the Defence Research Group and all of the participants, I would like to express our sincere thanks to the Canadian Department of National Defence and to Dr Schofield, for hosting this Seminar, Mr Pierre Yansouni and colleagues, Mr Blair and Mr Pilon for their efforts in organising the Seminar. The organization of a high-quality technical Seminar is not a simple task, and I am sure we are all grateful to Mr Yansouni and his Organization Committee for the many weeks of work they have devoted to this seminar of our behalf. We also appreciate the excellent facilities which have been made available by the Canadian Department of External Affairs here in the Lester Pearson Building.

To help set the framework for this Seminar, I would like to say a few words about the Defence Research Group, or DRG. During the reorganization of the committee structure at NATO in 1961 to 1967, the DRG was established as one of the four Main Groups under the Conference of National Armaments Directors, the CNAD. The other three Main Groups were the NATO Army, Navy and Air Force Armaments Groups. The establishment the Defence Research Group as one of these four primary bodies underlines the importance of research in the defence support structure of NATO.

Collaboration in defence R&D is of major and increasing importance to all the NATO Nations. This is especially true at a time when the principal threat to NATO nations is diminishing, and perhaps being replaced by new threats from new directions, resulting in greater pressure than ever to achieve maximum value for money from national defence budgets. The Terms of Reference of the Defence Research Group call for exchange of information, and the development of co-operative research programmes, which might lead to future joint developments of military equipment.

In attempting to promote collaborative research activities, it is essential to identify topics for bi- or multi-lateral co-operation with both a high level of military interest, and a promise of technological benefit. The Seminars of the Defence Research Group provide one means of reviewing such promising areas. Since its establishment in 1967, the DRG has held 29 Seminars, the current one being the 30th. These seminars have covered a very broad range of important topics or problems in defence research and technology, including such diverse subjects as oceanography, communications, terminally guided weapons, the military implications of sleep research, and military use of helicopters.

Another principal avenue of activity pursued by the DRG is provided by its Panels and Research Study Groups, or RSGs. These bodies bring together professionals who are experts in specific technology areas for exchange of information and collaborative studies, investigations and field trials. The Defence Research Group currently has 8 Panels, two Special Groups of Experts, and about 50 Research Study Groups. The Panels cover specific areas of technology or systems, and are long-lived bodies of a managerial nature. The RSGs, on the other hand, are set up to address a specific problem. The average working span for such a project is typically 3 to 4 years. The national participation in the RSGs varies between 4 and 11 nations. The Defence Research Group believes that the fact that nations continue sending experts to participate in its activities is an important indication of the DRG's value.

The subject of our Seminar is a vitally important and highly topical subject. I look forward to being educated in the complex interactions of Threats, Sensors, Weapons, Signatures and C2, during our Seminar this week.

Let me conclude by again expressing our gratitude to Mr Yansouni and his colleagues for taking on the heavy load of organizing this Seminar. We all know that this is a very time consuming task and we thank you. We look forward to a productive and informative Seminar.

CMDO KEYNOTE ADDRESS

TO THE

NATO DEFENCE RESEARCH GROUP (DRG)

30TH SEMINAR ON THE "DEFENCE OF

SMALL SHIPS AGAINST MISSILE ATTACKS"

CONFERENCE CENTRE (EXTERNAL AFFAIRS)

OTTAWA, CANADA - 12 SEPTEMBER, 1990

INTRODUCTION

BONJOUR MESDAMES ET MESSIEURS ET SOYEZ LES BIENVENUS À OTTAWA. C'EST AVEC PLAISIR, EN TANT QUE CHEF DES DOCTRINES ET OPÉRATIONS MARITIMES, QUE JE PROFITE DE CETTE OCCASION POUR FAIRE UN SURVOL OPÉRATIONEL SUR LA DÉFENSE DES PETITS NAVIRES; PAR LÀ J'ENTENDS LES NAVIRES DE 450 (QUATRE CENT CINQUANTE) À 4500 (QUATRE MILLE CINQ CENTS) TONNES, CONTRE LES ATTAQUES DE MISSILE. CECI EST UN ASPECT IMPORTANT POUR TOUTES LES NATIONS REPRÉSENTÉES ICI ET ÉTANT DONNÉ LES ÉVÈNEMENTS RÉCENTS DANS LE GOLFE PERSIQUE, C'EST UN SUJET PARTICULIÈREMENT PERTINENT. DE PLUS, COMME PRÉSIDENT DU GROUPE DES ARMEMENTS NAVALS DE L'OTAN, JE SUIS PROFONDÉMENT INTÉRESSÉ AUX RÉSULTATS DE CE SÉMINAIRE.

TOILE DE FOND (BACKGROUND INFORMATION)

LA POLITIQUE MONDIALE EST ENTRÉE DANS UNE PÉRIODE OU LE CHANGEMENT EST LA NORME. LE MOUVEMENT VERS LA DÉMOCRATIE EN EUROPE DE L'EST A ÉTÉ DES PLUS REMARQUABLES. L'UNIFICATION DE L'ALLEMAGNE S'EST RÉALISÉE ET IL Y A DE NOUVEAUX GOVERNEMENTS DÉMOCRATIQUES DANS VIRTUELLEMENT TOUS LES PAYS DU PACTE DE VARSOVIE. MÊME SI CES DÉVELOPPEMENTS FURENT POUR LA PLUPART PACIFIQUES, IL N'Y A AUCUNE GARANTIE QUE CELA VA CONTINUER DE LA MÊME FAÇON. DE PLUS, CECI NE S'APPLIQUE PAS DANS LE MONDE ENTIER. EN FAIT, PLUSIEURS SONT D'AVIS QUE LE MONDE AUJOURD'HUI EST PLUS INSTABLE ET COMPLEXE QUE JAMAIS ET QUE CELA VA CONTINUER JUSQU'A CE QU'UN ÉQUILIBRE CONVENABLE SOIT ATTEINT.

PLUSIEURS S'INTERROGENT MAINTENANT SUR LA NÉCESSITÉ D'UNE MARINE, MAIS AUSSI LONGTEMPS QUE LES MATIÈRES BRUTES ET LES AUTRES COMMODITÉS COMMERCIALES SERONT TRANSPORTÉS PAR DES NAVIRES MARCHANDS, ELLES AURONT BESOIN D'ÊTRE PROTÉGÉS CONTRE LES ATTAQUES. ET NATURELLEMENT, ON A TOUJOURS DEMANDÉ AUX MARINES D'ALLER OU C'ETAIT NÉCESSAIRE POUR DÉFENDRE LES INTÉRÊTS DE LEURS NATIONS.

THE FORMERLY BI-POLAR WORLD IS EVOLVING INTO A MULTI-POLAR WORLD WITH THE EMERGENCE OF OTHER COUNTRIES AND GROUPS AS THREATS TO THE WORLD STABILITY AND PEACE. MAJOR CONFLICT BETWEEN THE SUPERPOWERS HAS BEEN REPLACED BY THE MID-INTENSITY CONFLICT AS THE MOST LIKELY SCENARIO WHERE OUR SHIPS WILL COME INTO HARM'S WAY. DURING THE EIGHT YEAR IRAN-IRAQ WAR IT WAS NECESSARY FOR MERCHANT SHIPS TO BE ESCORTED THROUGHT THE HIGH RISK AREAS BY FRIGATES AND DESTROYERS. THE ECONOMIC SANCTIONS AND OTHER ACTIONS MADE NECESSARY BY IRAQ'S INVASION OF KUWAIT IS ANOTHER EXAMPLE OF THE TYPE OF EMPLOYMENT THAT OUR NAVIES CAN EXPECT. OTHER TASKINGS MAY INCLUDE THE EVACUATION OF CIVILIANS FROM AREAS OF CONFLICT, THE SUPPORT OF PEACEKEEPING EFFORTS BY PATROL CRAFT, AND MINE CLEARANCE. THE DEPLOYMENT OF SHIPS TO THE PERSION GULF HAS EMPHASIZED TO NATIONS SUCH AS CANADA THAT THEY MUST TAKE A BALANCED APPROACH TO WARFARE AND NOT CONCENTRATE ON ANY SPECIFIC AREA.

DESPITE THIS, ALL NATO NATIONS ARE EXPERIENCING PRESSURE TO REDUCE THEIR DEFENCE SPENDING. THE NOTION OF A "PEACE DIVIDEND" IS ONE THAT YOU ARE FAMILIAR WITH AND ONE THAT ALL COUNTRIES WILL HAVE TO ADDRESS IN THE COMING YEARS. THIS AT A TIME WHEN WEAPONS SYSTEMS ARE INCREASING IN BOTH SOPHISTICATION AND COST. THE NEED FOR COOPERATIVE MULTI-NATONAL RESEARCH AND DEVELOPMENT AND PROCUREMENT HAS NEVER BEEN MORE PRESSING.

TODAY MANY COUNTRIES ARE ARMED WITH SOPHISTICATED, HIGHLY TECHNICAL STATE OF THE ART WEAPONS. THERE ARE PRESENTLY SIXTY-SIX COUNTRIES THAT POSSESS AN ANTI-SHIP MISSILE CAPABILITY. THESE MISSILES ARE THE PRIMARY THREAT FOR SHIPS TODAY AND ARE PREDICTED TO REMAIN SO FOR THE FORESEEABLE FUTURE. AS YOU WELL KNOW, A SINGLE MISSILE CAN INFLICT CONSIDERABLE DAMAGE OR DESTROY A SMALL SHIP. IN RECENT YEARS THERE HAVE BEEN A NUMBER OF UNFORTUNATE EXAMPLE OF THEIR DESTRUCTIVE POWER. SAILORS HAVE BEEN KILLED AND SHIPS HAVE BEEN SUNK OR SEVERELY DAMAGED. THE THREAT FROM ANTI-SHIP MISSILES IS SIGNIFICANT NO MATTER WHAT AREA OF THE WORLD SHIPS HAVE TO OPERATE IN. THAT IS WHY, FOR EXAMPLE, THE CANADIAN SHIPS THAT WERE DEPLOYED TO THE PERSIAN GULF HAVE BEEN SPECIFICALLY EQUIPPED TO COUNTER THE ASM THREAT.

LA MENACE FUTURE

LA TECHNOLOGIE ASM PROGRESSE RAPIDEMENT. NOUS AVONS DÉJÀ VU DES AMÉLIORATIONS DANS LES TÊTES CHERCHEUSES ET LES PORTÉES, DES RÉDUCTIONS DANS LES SECTIONS RADAR ET LES ÉMISSIONS INFRA-ROUGE ET LES CAPACITÉS DE RÉ-ATTAQUER. D'AUTRES AVANCEMENTS INCLUENT DES AMÉLIORATIONS EN FURTIVITÉ, VITESSE, AUTOPROTECTION, CONSTANTE ALTITUDE, RECONNAISSANCE ET DISCRIMINATION DES CIBLES, CONTRE-CONTRE-MESURE ÉLECTRONIQUE ET MANOEUVRABILITÉ.

THE OPERATIONAL REQUIREMENT

EXISTING MISSILE DEFENCE TECHNOLOGY FOR SMALL SHIPS IS LAGGING BOTH THE PRESENT AND FUTURE ANTI-SHIP MISSILE THREAT. THERE ARE SIGNIFICANT WEAKNESSES IN THE DETECTION AND ENGAGEMENT OF THESE THREATS. ANOTHER MAJOR PROBLEM IS THAT THERE IS LITTLE CONFIDENCE IN THE CAPABILITY OF SOFT KILL AT PRESENT AND AS A RESULT THERE IS A MUCH GREATER EXPENDITURE OF HARD KILL ASSETS THAN MAY BE NECESSARY OR DESIRABLE. FUTURE SYSTEMS MUST ENSURE THAT THE SOFT KILL SUCCESS RATE HAS THE CONFIDENCE OF THE USER ~~IS IMPROVED SO AS TO~~ IMPROVE THE MANAGEMENT OF HARD KILL RESOURCES. FURTHER THE COORDINATION OF HARD AND SOFT KILL MEASURES MUST BE IMPROVED CONSIDERABLY THROUGH THE DEVELOPMENT OF BETTER THREAT EVALUATION AND WEAPON ASSIGNMENT (TEWA) ALGORITHMS FOR SHIPS AND GROUPS OF SHIPS. AUTOMATED COMMAND AND CONTROL SYSTEMS ARE REQUIRED TO MINIMIZE BOTH REACTION TIME AND OPERATOR INPUT.

THE GENERIC PURSUITS AND CONSTRAINTS

HOW TO ACCOMPLISH THIS; IS THE QUESTION FACING MANY NATIONS TODAY. THESE SYSTEMS SHOULD BE MODULAR TO ALLOW FOR FLEXIBILITY AND EASE OF INSTALLATION. IT MAY NOT BE NECESSARY OR DESIRABLE TO FIT THE COMPLETE SYSTEM IN ALL SHIPS FOR ALL SCENARIOS. ESSENTIALLY NATIONS MUST HAVE THE ABILITY TO INCORPORATE MODULES AS REQUIRED. THE SYSTEMS

MUST BE SUFFICIENTLY ADAPTABLE TO ALLOW FOR INSTALLATION IN A WIDE RANGE OF VESSELS AND MUST BE SUPPORTABLE, RELIABLE, AND SURVIVABLE. PERHAPS THIS IS AN AREA WHERE THE REQUIREMENTS FOR MILSPEC EQUIPMENT CAN BE BALANCED AGAINST THE LATEST COMMERCIAL "OFF THE SHELF" EQUIPMENT, PARTICULARLY IN ELECTRONICS. NAVIES HAVE BEEN PAYING A PREMIUM FOR MILSPEC WHEN IN MANY CASES THE LESS EXPENSIVE AND READILY AVAILABLE COMMERCIAL EQUIPMENT WOULD HAVE BEEN MORE THAN SUFFICIENT. THE TRADE-OFFS BETWEEN MILSPEC AND COMMERCIAL EQUIPMENT NEED TO BE STUDIED FURTHER TO DETERMINE THE WAY AHEAD, BUT A CURSORY EXAMINATION WOULD SEEM TO INDICATE THAT THIS IS POSSIBLE IN MANY CIRCUMSTANCES.

WHAT DO I ENVISION THAT THIS FUTURE SMALL SHIP MISSILE DEFENCE SYSTEM WILL LOOK LIKE? FIRST OF ALL, IT WILL HAVE MULTIPLE SENSORS. THE SYNERGISM OF MULTIPLE SENSORS HAS BEEN RECOGNIZED AND MUST BE TAKEN ADVANTAGE OF. SIZE AND WEIGHT CONSIDERATIONS MAY REQUIRE THAT A SINGLE RADAR PERFORM ALL FUNCTIONS FROM SEARCH THROUGH TRACKING AND ILLUMINATION. INTEGRATED ELECTRONIC SUPPORT MEASURE SENSORS WILL BE NECESSARY TO COUNTER IMPROVEMENTS IN MISSILE SEEKERS AND THE REDUCED SIGNATURE AND TRANSMISSIONS ASSOCIATED WITH FUTURE ANTI-SHIP MISSILES. THE FULL SPECTRUM OF ELECTRO-OPTICAL SYSTEMS FROM INFRA RED THROUGH VISIBLE AND ULTRA VIOLET SENSORS WILL ALSO NEED TO

EXAMINED AND INCORPORATED INTO THE SENSOR PACKAGE. THESE SENSORS WILL FEED INTO A COMPLEX AND FULLY AUTOMATED COMMAND AND CONTROL CORE. THIS SYSTEM MUST BE ABLE TO ACCURATELY AND RAPIDLY RECOGNIZE THREATS TO THE SHIP, DETERMINE THREAT PRIORITIES, ALLOCATE RESOURCES TO COUNTER THESE THREATS, ASSESS THE SUCCESS OR FAILURE OF THESE ACTIONS, AND TAKE FURTHER ACTIONS AS NECESSARY TO ENSURE A HIGH PROBABILITY OF SUCCESS.

FURTHER, THERE MUST BE THE ABILITY TO MONITOR THE OVERALL SYSTEM, INCLUDING THE HUMAN OPERATORS, INPUT AND ADJUST THE ACTIONS AS NECESSARY TO COMPENSATE. I WOULD LIKE TO EMPHASIZE THE NECESSITY TO ALSO INCLUDE TRAINING FUNCTIONS IN THIS SYSTEM. THE INCREASED COST OF LIVE WEAPON FIRINGS AND THE INABILITY TO ADEQUATELY REPLICATE THE THREAT MAKE THE REQUIREMENT TO INCLUDE STIMULATION AND SIMULATION A VITAL ASPECT OF ANY NEW SYSTEM.

THE WEAPONS ASSOCIATED WITH OUR SYSTEM WILL INCLUDE BOTH HARD KILL AND SOFT KILL ELEMENTS. THESE ELEMENTS WILL PROVIDE MULTIPLE LAYERS OF DEFENCE AND MINIMIZE MUTUAL INTEFERENCE BETWEEN ELEMENTS TO ALLOW FOR ENHANCED COORDINATION AND EFFECTIVE MANAGEMENT OF ASSETS. FORCE TEWA OR THE COORDINATIONAL OF SEVERAL SHIPS' ASSETS ALSO NEEDS TO BE FURTHER DEVELOPED.

CONCLUSION

EN CONCLUSION, LES PRESSIONS POUR LA RÉDUCTION DES FORCES MILITAIRES VONT AVOIR BESOIN D'UNE MEILLEURE COOPÉRATION ENTRE LES MARINES ALLIEÉS. EN DÉPIT DE LA RÉDUCTION, LES MARINES DEVRONT ENCORE SERVIR LES INTÉRÊTS NATIONAUX A TRAVERS LE MONDE. JE VEUX SOULIGNER QUE LES LEÇONS TIRÉES DE LA RECHERCHE ET DU DÉVELOPPEMENT COOPÉRATIFS PENDANT LE PROGRAMME NFR 90 NE DOIVENT PAS ÊTRE OUBLIÉES. PLUSIEURS RÉUSSITES ONT PROUVÉ LA VALEUR DE LA COOPÉRATION DANS CE PROJECT MÊME SI LE MALADE EST MORT.

MY CHALLENGE TO YOU, THE DEFENCE RESEARCH GROUP, IS TO RECOGNIZE THAT THE NEED FOR COOPERATION IN RESEARCH AND DEVELOPMENT IS PARAMOUNT; THAT INTEROPERABILITY OR COMPATIBILITY, RELIABILITY, AND AFFORDABILITY ARE KEY WORDS FOR THE FUTURE. MAY I WISH YOU MUCH SUCCESS IN YOUR SEMINAR. FROM MY PERSPECTIVE AS A CANADIAN NAVAL REQUIREMENTS OFFICER AND AS CHAIRMAN OF NNAG, I LOOK FORWARD TO THE OUTPUT OF YOUR WORK IN THIS VITAL FIELD OF R&D.

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14. Abstract: In order to maximize the defence of a warship against aircraft and anti-ship missile attacks, it is necessary to coordinate the use of all available defensive weapon systems. These systems may consist of hardkill weapons such as missiles, guns, or close-in-weapon systems, and softkill weapons such as on-board jammers, off-board decoys, or chaff. The coordination of hardkill and softkill weapons provides several advantages, including reduction of hardkill assets expenditure and increase in ship's survivability.

The development of coordination concepts and techniques requires a good understanding of the tactical environment (i.e. attack scenarios and threat characteristics), as well as a detailed knowledge of hardkill and softkill weapon performances. Computer simulation models represent a cost effective approach to the evaluation of these techniques. Within the context of the NATO AAW System program, a computer model was developed to evaluate various hardkill/softkill weapons coordination techniques in specified scenarios. Simulation results demonstrate that a significant improvement in ship's survivability can be achieved by timely and coordinated deployment of chaff against hardkill and softkill weapons. The simulation model can provide insights useful for the design of a comprehensive weapons integration system.

NATO DEFENCE RESEARCH GROUP SEMINAR

DEFENCE OF SMALL SHIPS AGAINST MISSILE ATTACKS

CONFERENCE CENTRE, DEPARTMENT OF EXTERNAL AFFAIRS

125 SUSSEX DRIVE, OTTAWA, ONTARIO K1A 0G2

THURSDAY, 13 SEPTEMBER, 1990
1400 HRS

HARDKILL/SOFTKILL WEAPONS COORDINATION

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HARDKILL/SOFTKILL COORDINATION STUDY MANDATE

DREO was tasked to participate in the Hardkill/Softkill Coordination Splinter Number 3-1-49, of the Concept Exploration (CE) Phase of the NATO Anti-Air Warfare System (NAAWS) project. In this Phase, government defence scientists from the NAAWS countries were grouped into splinters to study different assigned areas of interest. The members of 3-1-49, drawn from the US, UK, the Netherlands and Canada, considered that we were to determine if coordination of hardkill and softkill could increase the survival of the Force, the NAAWS and defended ships, as defined in the NAAWS Scenarios for the CE Phase. We were further charged to identify instances of interference and to recommend measures for its avoidance.

Canada offered to model this coordination using the softkill ship defence simulation developed at DREO, ASMD, together with the hardkill simulation TACSIT, a property of Thomson-CSF Systems, Canada. The model would be exercised in the NAAWS Scenarios. This offer was accepted. Since the system had not yet been defined, it was necessary to define candidate hardkill and softkill systems for this purpose, together with the electronic warfare (EW) characteristics of the assumed threat. Generic system parameters were used, so that this modelling represents a hypothetical system and tactic.

NATO ANTI-AIR WARFARE SYSTEM (NAAWS)

The NATO Anti-Air Warfare System consists of both hardkill and softkill weapon assets deployed in the defence of a maritime force against missile attack. The NAAWS countries are a sub-set of the NATO nations, developing the system co-operatively. The coordinated deployment of softkill and hardkill was a significant feature of the system as originally conceived. The overall system consists of a mixture of NAAWS and national variant components, presenting a system design and specification challenge. The nationally variant components are those for which it was felt that current national investments would not allow replacement with NAAWS components. The NAAWS specified elements are:

- Multi-Function Radar (MFR)
- Infra-Red Search and Track (IRST)
- Local Area Missile (LAM)
- Core
- Precision ESM (PESM)

while the national variant components are:

- Volume Search Radar (VSR)
- ESM system
- Close In Weapon System (CIWS)
- Softkill Weapons (SK).

The precision ESM NAAWS component is possibly required to augment the national ESM capability in order to meet the angular precision requirements for ESM to cue the MFR. The NAAWS structure is given in Fig. 1. The sensors including the IRST, the MFR, the VSR and the ESM capability are controlled and their outputs integrated in the Core by the Sensor Integration and Control (SI&C) function. All weapons, both hardkill, the LAM and CIWS, and the softkill countermeasure assets, are controlled in the Core by the Weapon Direction and Control (WD&C) function. The Core also includes a Local Command and Control (LC&C) function as well as a Readiness and Training (R/T) function.

NAAWS HYBRID HARDKILL/SOFTKILL SIMULATION

Both ASMD and TACSIT, and hence the hybrid simulation represent random effects by the use of pseudo random numbers. Average system performance in a given scenario is derived from exercising the system simulation in repeated Monte-Carlo runs. The hybrid simulation developed for this modelling work is depicted in Fig. 2.

The TACSIT portion of the NAAWS hybrid simulation is exercised by target information provided by ASMD through the interface to TACSIT. Because threat trajectory is a result of the effect of the skin return and jamming (SK) on the threat seeker, the threat trajectories in each Monte Carlo run are determined in ASMD from the combined signals, the seeker processing and resulting missile response.

The hardkill component of the NAAWS hybrid simulation, TACSIT, models the MFR and ESM sensors, the CORE, and the hardkill LAM and CIWS. The MFR segment simulates the surveillance, target detection, and track creation and maintenance functions of the NAAWS sensors as well as the uplink target data provided by the MFR to the LAM during midcourse guidance. Support of the LAM during its terminal homing phase is provided by either one of two separate illuminators located forward and aft on the NAAWS ship. Blind zones due to ship superstructure or the unavailability of one of the two illuminators can result in critical engagement time lines for the use of the LAM. The ESM model simulates the detection of an emitter and determination of its range, bearing, identity and radar mode as well as the creation, update and dropping of tracks by the ESM system. The fusion of MFR and ESM data takes place within the CORE. In the TEWA model tracks are ranked, and softkill and hardkill weapons are assigned to threats. Target tracking for a hardkill engagement is modeled as well as the deployment of a weapon system, the flight of its ammunition, either gun shells or ownship missile, and the result assessment process after the ammunition intercepts its target. The CIWS is autonomous, including its target detection, track processing, TEWA function, fire control radar tracking, firing and shell flight. Interference effects of chaff on LAM missions and upon MFR and CIWS radar detection capability are also determined.

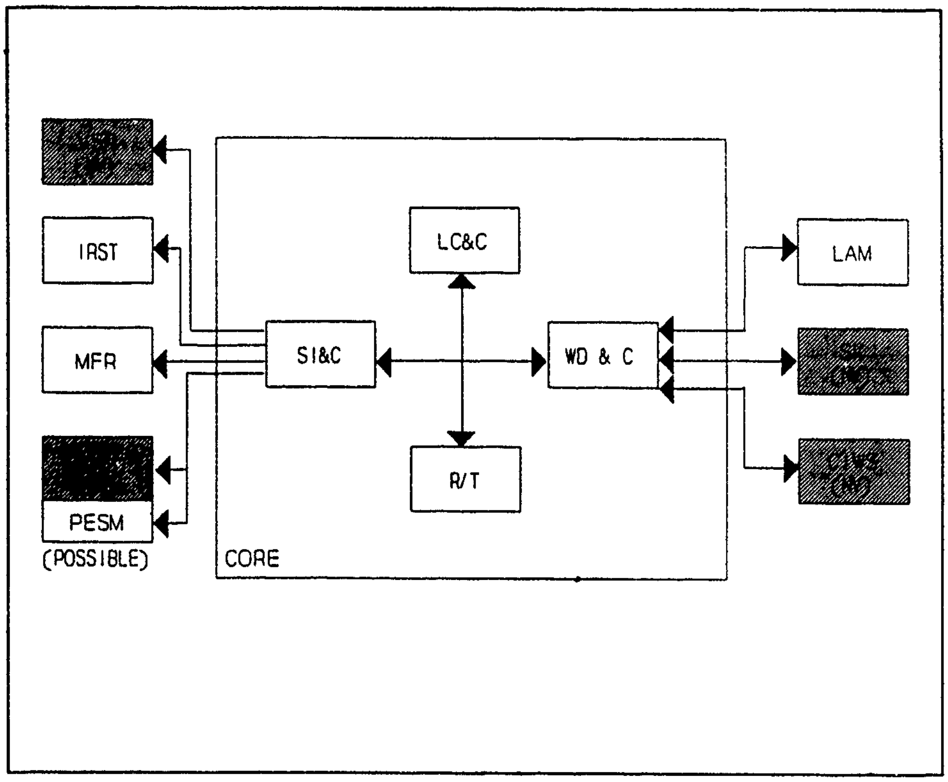

Figure 1: NAAWS STRUCTURE

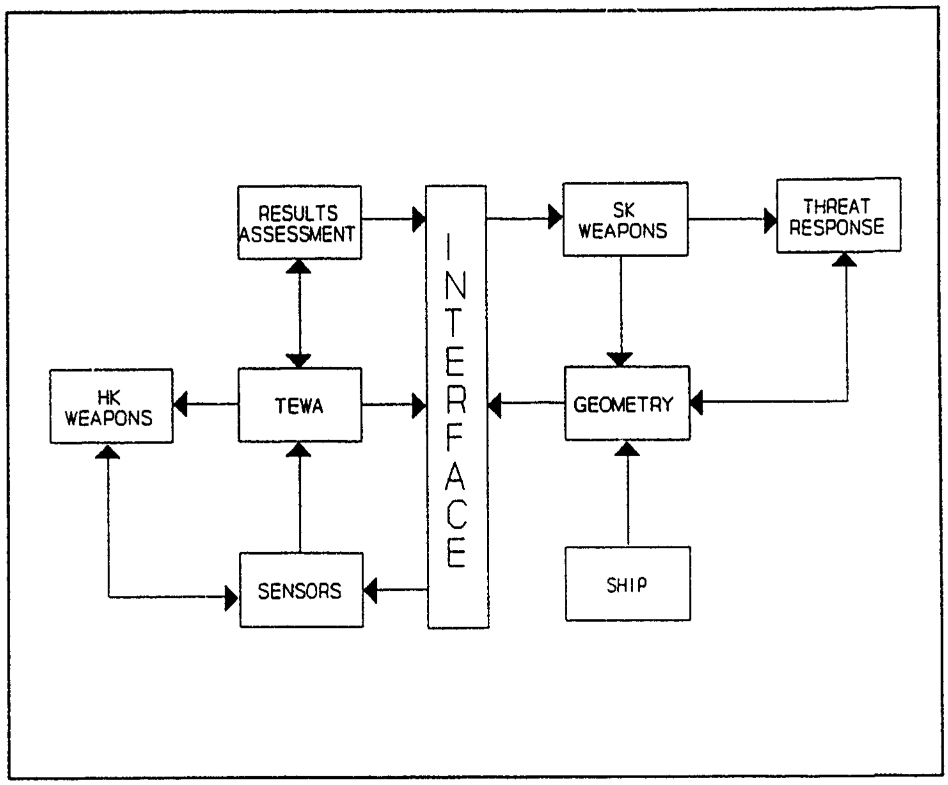

Figure 2: ASMD / TACSIT HYBRID MODEL

The ASMD simulation models ship motion and ship signature. The signature model consists of a number of scatterers at specified locations on the ship frame. Their amplitudes vary randomly about a mean value which is a function of ship aspect. The random values are filtered so that the resulting scintillation fluctuations represent the appropriate ship signature bandwidth. Since the scatterers are separated in space, the vector addition of their returns in amplitude and phase produces both scintillation and the appropriate directional fluctuations, or glint. ASMD provides a range of possible combinations of softkill platforms and payloads. Chaff is launched from the ship at specified angles; it bursts, then blooms and decays exponentially in mean value. Rayleigh-model scintillation using chaff bandwidth is calculated and superimposed on the chaff mean value. Other payloads can be similarly launched with parachute descent, to rest and float on the surface of the sea or can be placed over the side of the ship to either float freely or be towed after the ship. Onboard and offboard jamming can include noise, repeaters or transponders.

HYBRID TEWA CHARACTERISTICS

In designing the hybrid TEWA control process it was found that analogous functions exist for both types of weapon. These are summarized in the following table.

TABLE 1: WEAPON CONTROL FUNCTIONS FOR SOFTKILL AND HARDKILL

HARDKILL	SOFTKILL EQUIVALENT
THREAT	THREAT
WEAPON	SOFTKILL OR SOFTKILL COORDINATION TECHNIQUE, MAY INCLUDE ACTIVE TECHNIQUE
AVAILABILITY	AVAILABILITY, TIME TO DEPLOY OR TO HAVE EFFECT, INTERFERENCE CHECK
EFFECTIVENESS PREDICTED	EFFECTIVENESS IS A COMPLEX FUNCTION OF MANY DATA

While the threats are identical, the softkill equivalent to the list of hardkill assets includes all possible softkill techniques that could be deployed with the available assets. These techniques include those using single or multiple softkill assets, or softkill assets in coordination with hardkill assets. Since the techniques use softkill, in order to predict their probability of success, effectiveness algorithms and data for each candidate technique are required from either previous trials or validated modelling. This area is largely unexplored, depending on knowledge of the threat and of specific system performances, data that each country protects for its own systems.

The NAAWS TACSIT TEWA model supports the coordinated and uncoordinated use of hardkill and softkill weapons. Threat ranking is based upon such parameters as track identity, seeker mode and the closest point of approach (CPA), and time to impact with respect to each ship. Assignment of weapons to threats is based on weapon's availability, engageability, predicted effectiveness or probability of kill and the presence of interference with other subsystems. Hardkill engageability for the LAM depends on system reaction time, engageability envelope, availability of MFR and illuminator support, and LAM storage level. Softkill engageability depends on such factors as threat radar mode, time to burnthrough, deployment time, time for the countermeasure to have an effect, available duty cycle, softkill store level and impact of the countermeasure deployment upon the Force. If the softkill countermeasure under evaluation is deemed to pose a menace to the Force, it is either deactivated or considered not engageable. Hardkill and softkill weapons are assigned to tracks that are engageable by them for either coordinated or non-coordinated use. Parameters used in this process include threat ranking, predicted effectiveness values and interference. Hardkill results assessment is performed during a window of time centred on the predicted time of intercept and simulates the time needed for this function. Softkill results assessment is based upon predicted CPA of the track with respect to each ship or deployed countermeasure and observed threat radar mode changes.

TYPES OF COORDINATION

The simplest case occurs when there is no area of overlap between proposed techniques, so that their deployment and results bear no reference to each other. These deployments are completely independent.

Minimal coordination occurs when techniques which can affect each other are deployed in such a way as to avoid interference between them. An example would be the use of chaff while taking care not to cross sight lines for visual or radar tracking.

Beyond these types is coordination where some benefit can be generated by related use. In non-contingent coordination, the entire coordination technique is pre-set and does not require mid-term results assessment for determining its completion. An example of non-contingent coordination would be the use of softkill to alter threat trajectories from their original non-softkill paths to trajectories in areas of higher hardkill effectiveness. The sequence of the coordinated technique is unchanged whether or not the lure to higher lethality has been successful. A contingent use of coordination occurs when intermediate results assessment data affect technique completion, as when the apparently successful decoy deception of a given threat allows reduction of the rank of the decoyed threat in the threat evaluation ranking, and hence an ultimate possible conservation of hardkill assets. The degree of confidence in both the softkill technique and the determination of

its success can determine the amount of threat rank reduction: for little confidence, reduction could be slight; for greater certainty of softkill success a greater threat rank reduction could be used.

A SAMPLE COORDINATION TACTIC

The scenario exercised is depicted in Figure 3. The Force F consists of N, the defending ship, and ships S1 and S2 which are all proceeding towards the East. Multiple missiles are launched in rapid succession from behind the ships at L. Targeting of the missiles is distributed among the three target ships and repeats from run to run. The lines depict the paths followed by the missiles towards their targeted ships. This is the scenario for the undefended Force; all threats are assumed to reach and destroy their targets. The threat assumed for this scenario acquires the target immediately after launch, and uses RF homing through the mid-course and terminal phases. This figure also serves for the Force defended by hardkill alone, since hardkill does not affect threat trajectory. With hardkill alone defending the Force, some missiles are destroyed before reaching their targets. Hardkill alone provides good defence of the N ship and less protection for the outlying escorted ships. In the assumed system, 1 out of 2 illuminators is available for LAM use, limiting the scope of the hardkill scheduler. As well, the engagement time line of the LAM, with much shorter engagement windows for outlying ships, contributes critically to hardkill performance. We sought to determine the improvement possible over this baseline performance by the coordinated use of softkill.

The coordination defence can be considered as the superposition of successive softkill actions. The initial softkill tactic is to begin noise jamming as soon as the N ship detects that missile launch is imminent. The effect of the initial softkill tactic is illustrated by the dashed trajectories in Figure 4. The missiles are unable to acquire their targets after launch due to the noise levels, and revert to home-on-jam mode. The missiles which were targeted on S1 and S2 and would otherwise home on these ships are turned in towards the N ship, the source of the jamming. Because of the jamming noise level, the threats are unable to acquire until burn-through range has been reached, where the skin return power level of the N ship starts to exceed that of the jamming noise power captured by the threat antenna. A small portion of the threats is assumed to be unaffected by the jamming; for such threats, the missile does not change to home-on-jam mode but continues as originally targeted, acquires the targeted ship at burn-through and homes on it. The main reason to draw in the S1- and S2-targeted threats towards the N ship is the longer engagement time windows for closing threats compared to outlying targets. This allows the hardkill system to better schedule LAM engagements against high threat density. Further, greater hardkill probability of kill (pk) is exhibited for closing targets as contrasted with crossing targets. The hardkill system on the

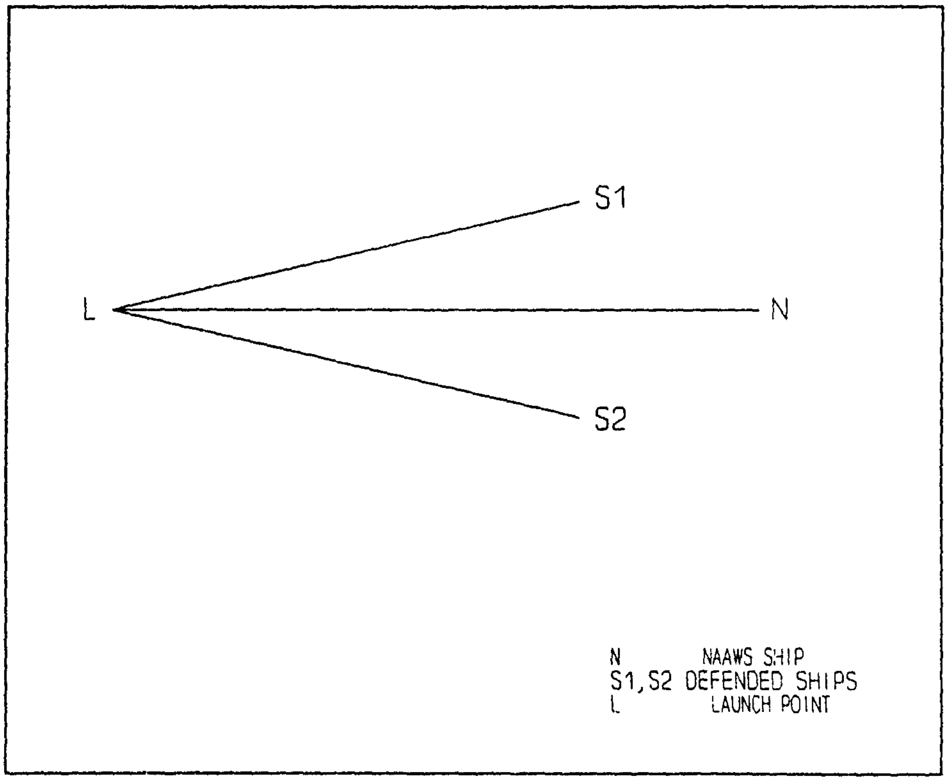

Figure 3: BASELINE SCENARIO

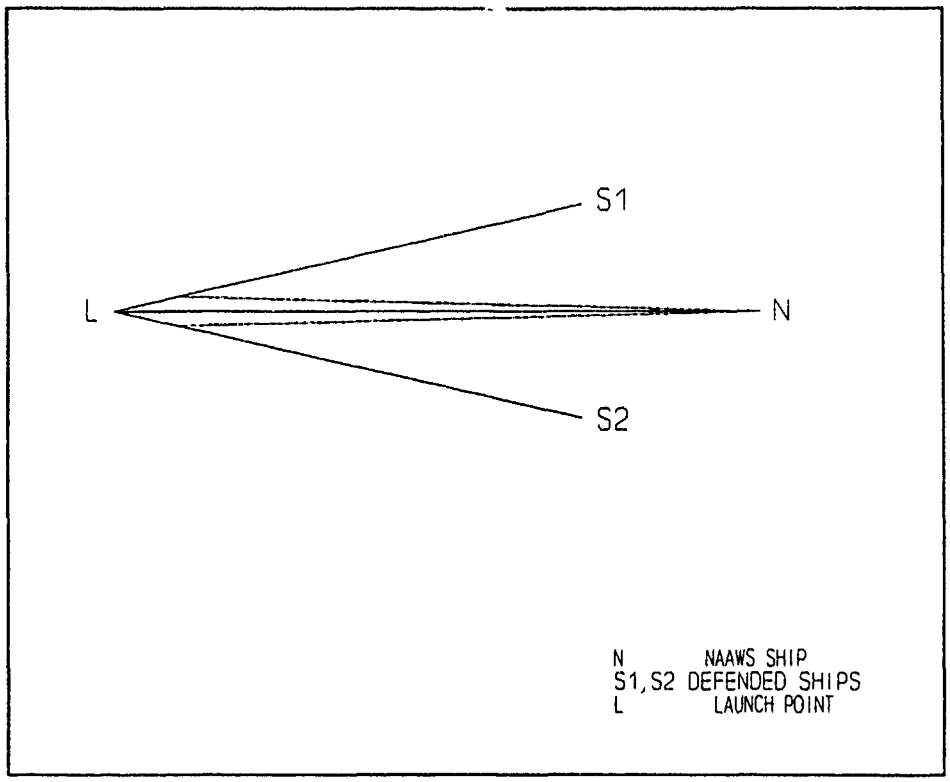

Figure 4: NOISE JAMMING ALONE

defending ship will destroy more of the engageable threats if these threats are closing on the defending ship rather than if they were proceeding towards the defended outer ships. Both factors, the higher proportion of threats engageable due to longer engagement windows, and the higher pk of the closing engageable threats, combine to produce enhanced hardkill performance. The effect on Force survival can be seen in Tables 2 and 3. Ships S1 and S2 survive more often at the expense of increased pressure on N, the defending ship. The first phase of the coordination tactic has succeeded in directing the attack to the Force ship which is able to defend it.

The second stage of the coordination technique is illustrated in the Figure 5. In this stage, the delay in threat target acquisition produced by the noise jamming provides sufficient time to deploy alternative targets. When the threat goes into acquisition and scans in azimuth about the expected target position, it can acquire the chaff or decoy that has been positioned in the interim. The placing of these alternate targets is crucial. They must be close enough to the N ship so that they are within the limited search scan used by the threat to acquire a pre-targeted victim; they must also be far enough removed from the N ship to provide a clear miss of the ship, with little chance of lock transfer back to the ship. The magnitudes of the alternative targets were chosen so as to compete successfully with the signature of the ship. Typical effects on Force survival of this provision of alternate targets are seen in Table 4. Taken together, these two results produce a net effective defence of the Force.

A further stage for single threats, or less than stressing scenarios, could be the use of onboard jamming techniques to break the lock of those threats still homing on the N ship. An onboard jammer capable of dealing separately with more than one threat, in the same band, in different modes could be used; passive techniques could also serve multiple threats.

CONCLUSIONS

From the results of the study, it is possible to draw a number of conclusions. First, the results are encouraging in that they demonstrate the benefits associated with the coordinated use of hardkill and softkill weapons. From detailed performance data of hardkill and softkill systems, it may be possible to derive coordination tactics that can produce performance greater than for their independent non-interfering use. The chief problem, however, is the accumulation of the required detailed tactical performance data for the design of coordination tactics, and reliable prediction of softkill or coordinated softkill effectiveness. Without these data and performance prediction algorithms, weapon control for combined hardkill and softkill cannot take advantage of possible coordination effectiveness.

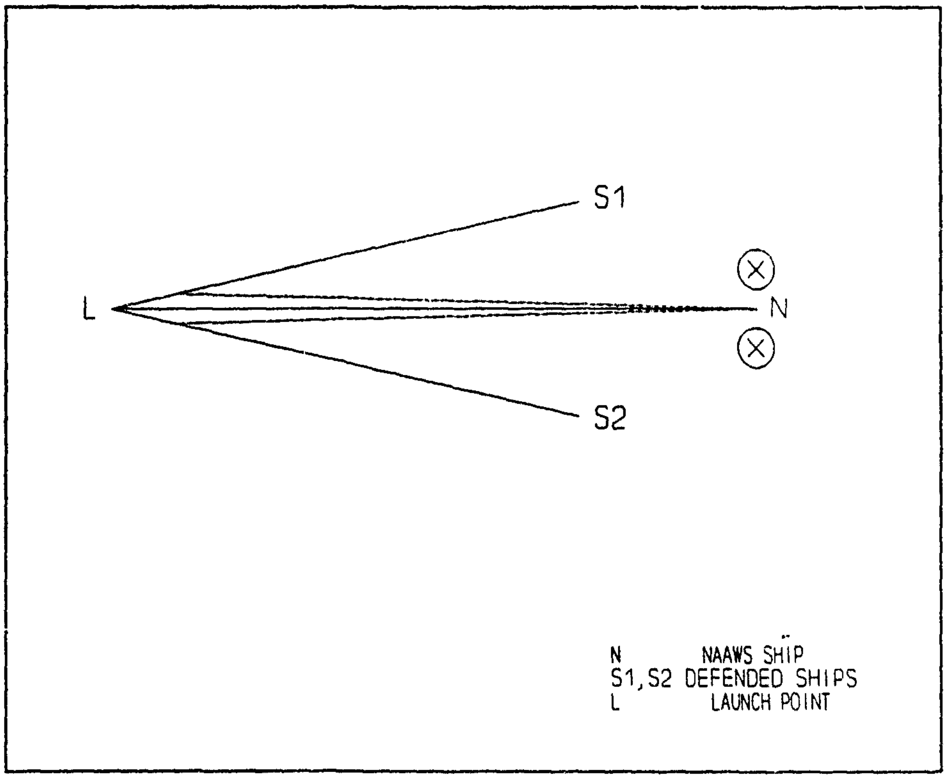

Figure 5: NOISE JAMMING AND ALTERNATIVE TARGETS

Ship	Prob. of Survival
N	0.88
S1	0.001
S2	0.48

TABLE 2: Force Survivability - HK alone

Ship	Prob. of Survival
N	0.12
S1	0.84
S2	0.80

TABLE 3: Force Survivability - HK and NJ

Ship	Prob. of Survival
N	1.00
S1	0.78
S2	0.80

TABLE 4: Force Survivability - HK and NJ / Chaff

Second, the simulation model used to derive the results has served to identify complex hardkill/softkill interaction mechanisms. As such, the model has proven to be a very useful tool for the analysis and assessment of hardkill/softkill coordination tactics. Further studies, building on this knowledge base, are recommended in order to augment understanding of complex hardkill/softkill coordination issues.

Such studies will serve as the point of departure for the specification and design of a hardkill/softkill weapons management system. Such a system would coordinate and control the use of hardkill and softkill resources onboard a naval platform. Several important issues, however, must be addressed before a comprehensive weapons manager can be developed. Such issues include the role of the weapons manager in the context of a naval command and control system, the interaction with the TEWA process, the level of automation and the interface with the tactical operators, the nature and the accuracy of the data required to perform the coordination and control function.

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13. Keywords/Descriptors: ASM DEFENCE, POINT DEFENCE, NEAR TERM, LONG TERM	
14. Abstract: The paper gives an overview of US Navy programme and objectives of anti-ship missile defence. Both evolutionary near term concepts, and advanced far term programmes are described.	

US NAVY TECHNOLOGY FOR FUTURE POINT DEFENSE SYSTEMS

14.1

Dr. Elihu Zimet
Office of Naval Technology

14.2

AGENDA

- **Introduction**
  - Rationale for focused Effort
  - Program Objectives
- **Approach**
- **Technology Concepts**
  - Evolutionary/ Near Term
  - Advanced/ Far Term

VISION FOR FUTURE NAVY

- REDUCED DOD FUNDING FOR ACQUISITION & DEPLOYMENT
- POTENTIAL FOR STRONG S&T BASE AS HEDGE AGAINST BREAK OUT
- REDUCED FOREIGN BASING
- MULTI-POLAR THREAT BASE INCLUDING THIRD/FOURTH WORLD
- MORE POTENTIAL FOR HOSTILITIES IN NEUTRAL TRAFFIC
- MORE POTENTIAL FOR HOSTILITIES CLOSE TO SHORE (RESTRICTED BATTLE SPACE)
- NEED TO PROTECT SHIPS NOT PART OF BATTLE GROUP - (TRANSPORT, LOGISTICS, AMPHIBIOUS ETC.)

14.3

POINT DEFENSE

THE CLOSE-IN DEFENSE OF ONE'S OWN SHIP

14.4

ATTRIBUTES

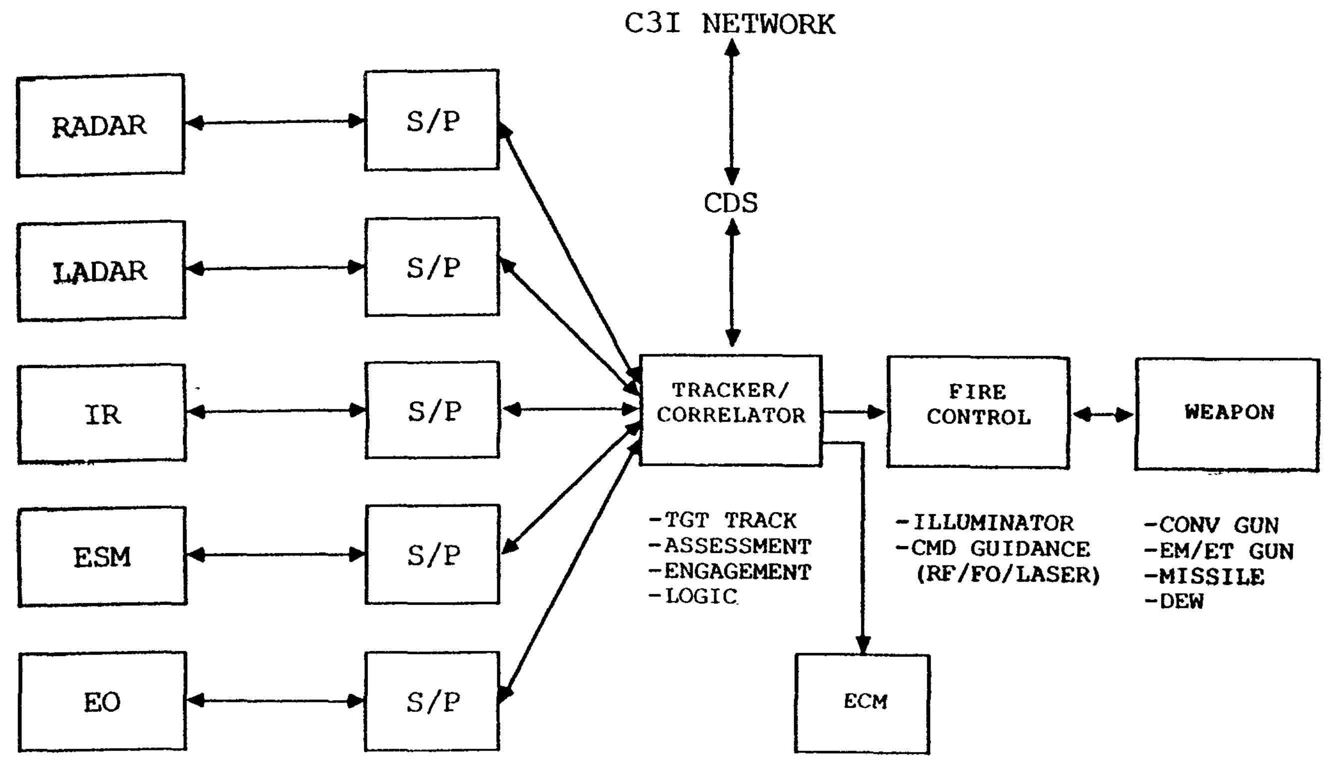
- KEEP-OUT RANGE LIMITED BY ACQUISITION HORIZON & TIME LINE IS AT MOST 5-6 MILES
- MAJOR THREAT IS ON-THE-DECK HIGH SPEED MISSILES
- P_k= 1 REQUIREMENT FOR SYSTEM; IF NOT, DAMAGE CONTROL
- NEED NOT COVER LOCAL AREA
- AIR TARGET ID NOT GENERALLY A PROBLEM DUE TO SHORT RANGE OF WEAPONS

14.4

NATO UNCLASSIFIED

AC/243-TP/2

GENERIC WEAPONS SYSTEM



NATO UNCLASSIFIED

14.5

POINT DEFENSE

14.6

NEAR TERM

- TO EXTENDED SERVICE LIFE OF CURRENT INVENTORY
- CONVENTIONAL CARRIER GROUPINGS (FEWER OF THEM)
- DEFENSE IN DEPTH - POINT DEFENSE COUPLED TO OUTER-AIR-BATTLE & AREA DEFENSE
- SINGLE ARCHITECTURE
- TECH FOCUS - INTEGRATION OF SURVEILLANCE, WEAPONRY, EW AND ADVANCED COMPONENT DEVELOPMENT

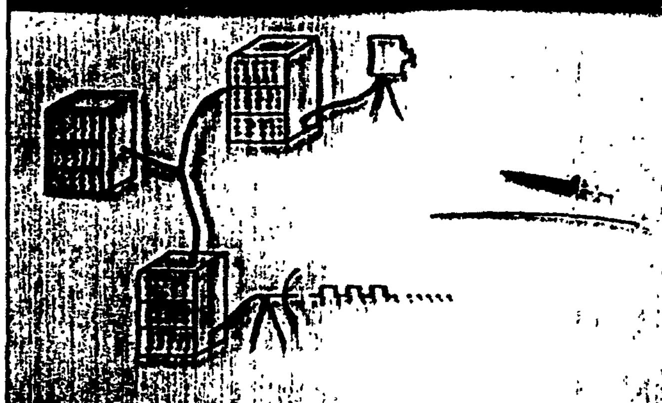
POINT DEFENSE

FAR TERM

- POSSIBLE NEW (SMALLER) BATTLE FORCE GROUPINGS AND DIFFERENT SHIPS
- STAND-ALONE POINT DEFENSE DESIRABLE FOR SOME SHIP CLASSES
- MULTIPLE OR MODULAR ARCHITECTURE
  - VALUE OF WEAPON TO MATCH VALUE OF SHIP
- SINGLE ARCHITECTURE
- TECH FOCUS - INTEGRATED SYSTEM ARCHITECTURES -- POINT DEFENSE WEAPON IS THE DRIVER

14.7

NEAR TERM



OBJECTIVE

- DEVELOP AND EVALUATE MULTI-SENSOR, MULTI-SPECTRAL TECHNIQUES WITH REPSECT TO HIGH PERFORMANCE SRAAW F/C
  - FOCUS ON LOW ALTITUDE TARGETS
  - FOCUS ON REDUCED OBSERVABLES/ECM
  - FOCUS ON RADAR/IR INTEGRATED SEARCH AND TARGET ACQUISITION

APPROACH

- ANALYSIS AND SIMULATION TO EVALUATE CANDIDATE SENSOR AND MSI TECHNOLOGIES/ TECHNIQUES
- CONDUCT EXPERIMENTS IN LABORATORY [illegible] TO QUALIFY TECHNOLOGIES AND TECHNIQUES FOR FURTHER WORK
- PROTOTYPE AND DEMONSTARTE PROMISING SENSOR AND MSI TECHNOLOGIES

MILESTONES

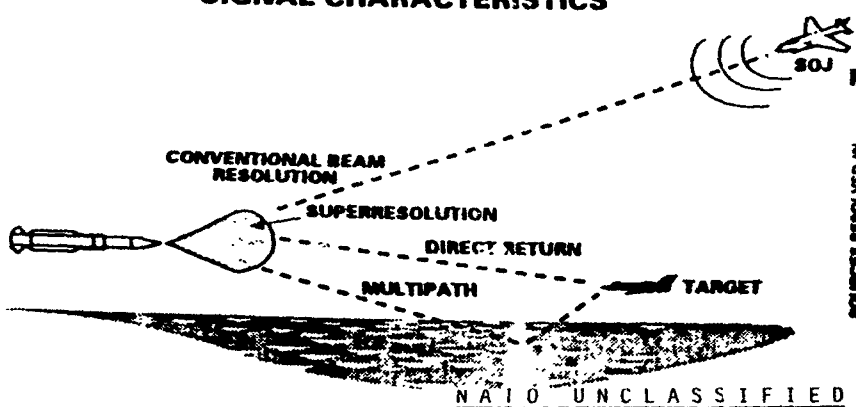
• MSD REQUIREMENTS DEFINITION	FY 89
• MSD SIMULATION OPERABLE	FY 90
• DATA COLLECTION/REQUIREMENTS VALIDATION	FY 91
• ACP FABILITY UPGRADE	FY 91
• NRT CONCEPT DEMONSTRATION	FY 92
• LIMITED RT CONCEPT DEMONSTRATION	FY 93

SENSOR AND PROCESSING TECHNOLOGIES

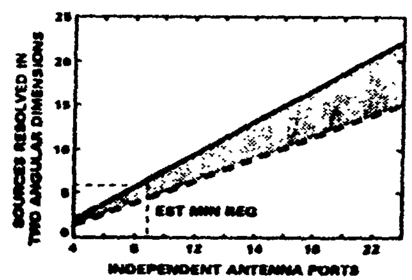
ADAPTIVE SUPERRESOLUTION ANTENNA

OBJECTIVE: DEVELOP PRACTICAL ANTENNA CONCEPT & SIGNAL PROCESSING TECHNIQUES FOR AN AAW MISSILE SEEKER TO:

- ENHANCE ANGLE RESOLUTION BY A FACTOR OF 3 OR BETTER
- RESOLVE & CLASSIFY MULTIPLE JAMMERS, TARGETS & MULTIPATH WITHIN SEEKER MAIN BEAM
- OPTIMIZE TARGET DETECTION AND HOMING IN INTERFERENCE
- TOLERATE SYSTEM ANOMALIES AND ARBITRARY SIGNAL CHARACTERISTICS



MULTIPLE SOURCE RESOLUTION



14.10

HIGH PERFORMANCE PD MISSILE
ADAPTIVE SUPERRESOLUTION ANTENNA TECHNICAL SPECIFICATION

RESOLUTION TO < 1/3 BEAMWIDTH IN MAINBEAM

RESOLVE UP TO 6 TARGETS/JAMMERS IN MAINBEAM

OPERATION IN MULTI-PATH

MAINBEAM INTERFERENCE SUPPRESSION > 20dB

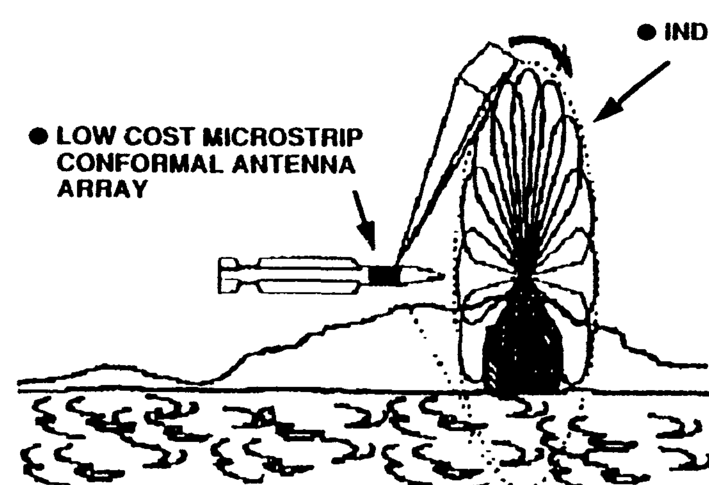
14.11

DIRECTIONAL ORDNANCE SYSTEM

UNCLASSIFIED

DIRECTIONAL ORDNANCE FUZE

BASELINE RF TDD CONCEPT

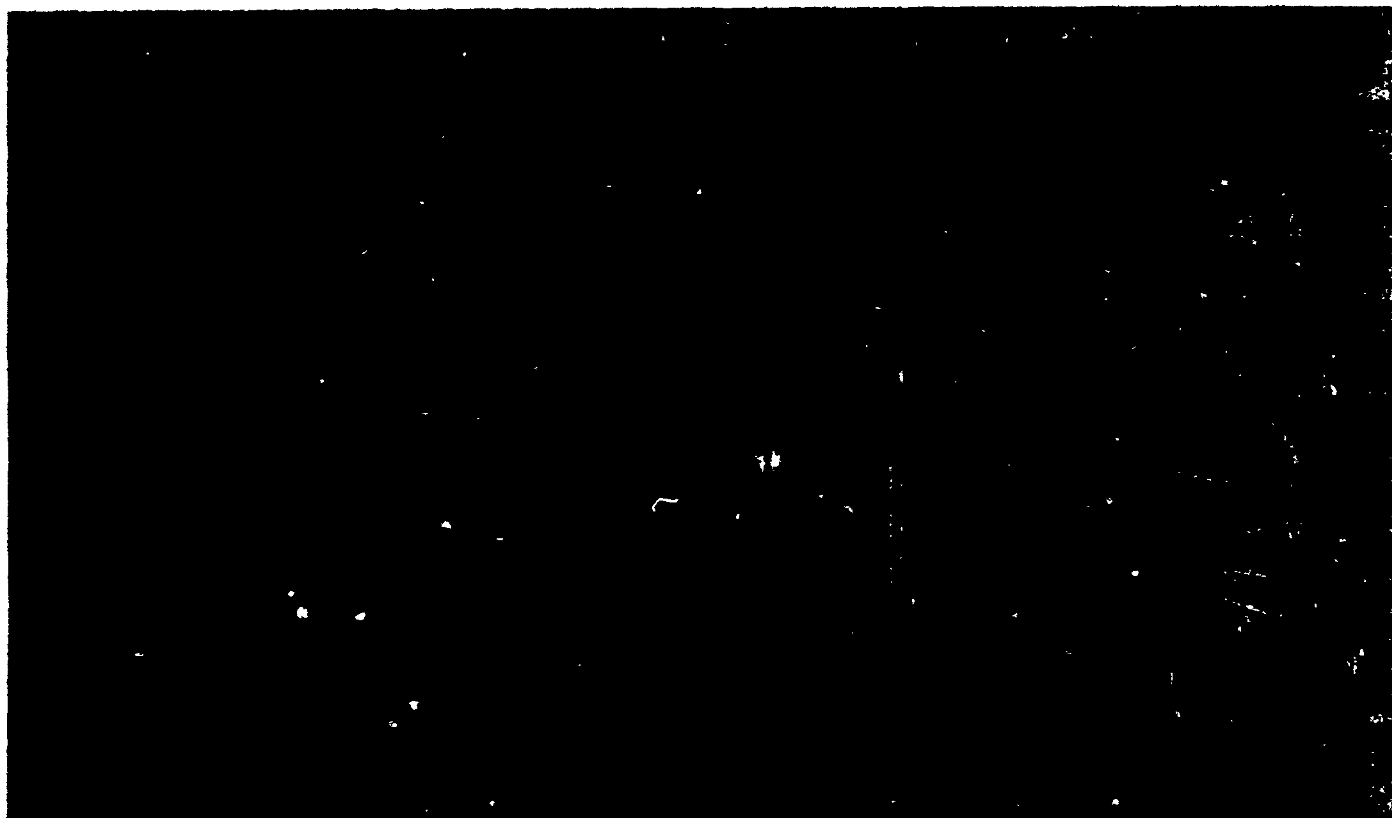


- LOW ALTITUDE ENCOUNTER
  - INDIVIDUAL RANGE CELL RETRACTION
  - MAINTAIN FULL AZIMUTH DETECTION

UNCLASSIFIED

14.12

14.13

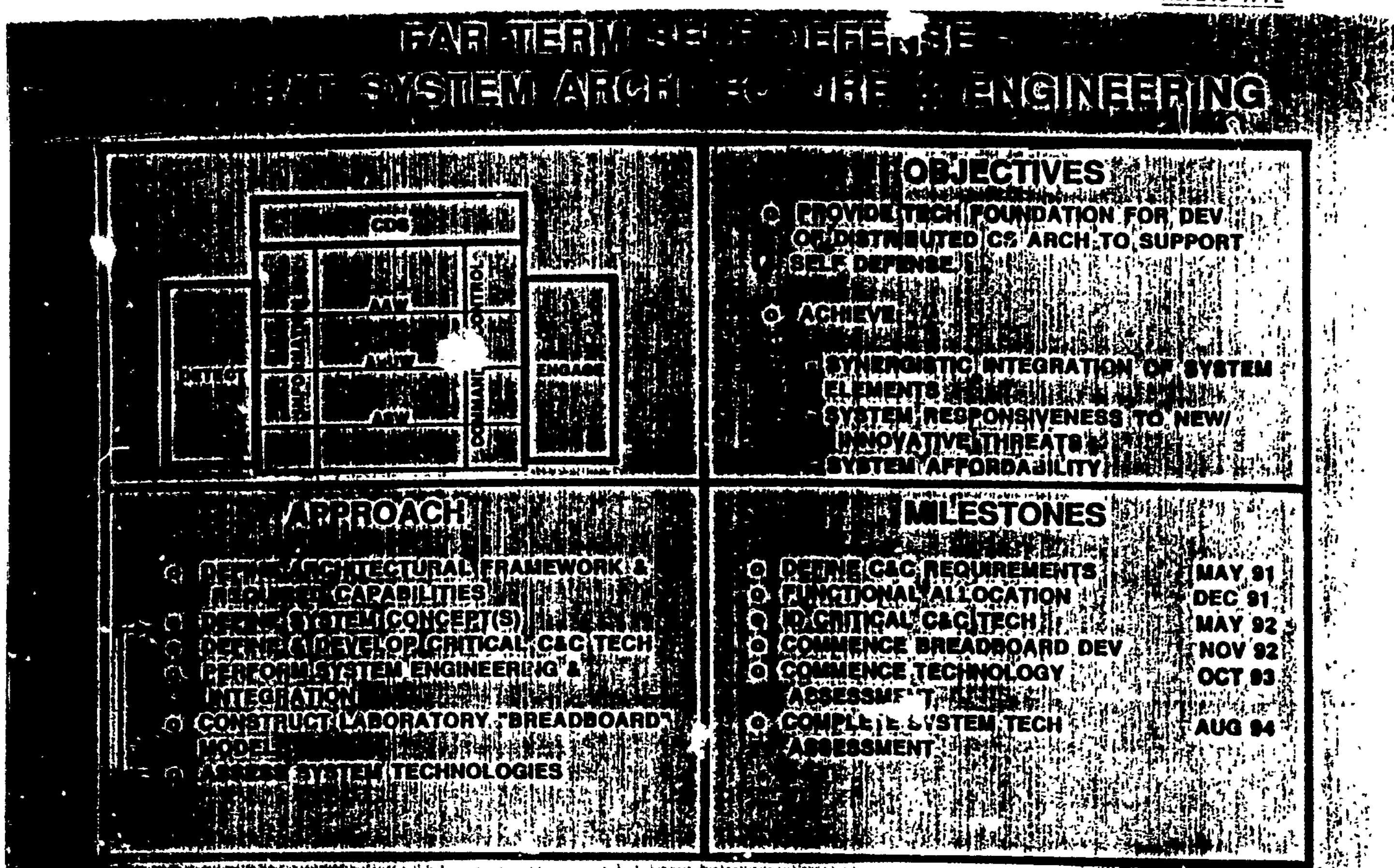


14.13

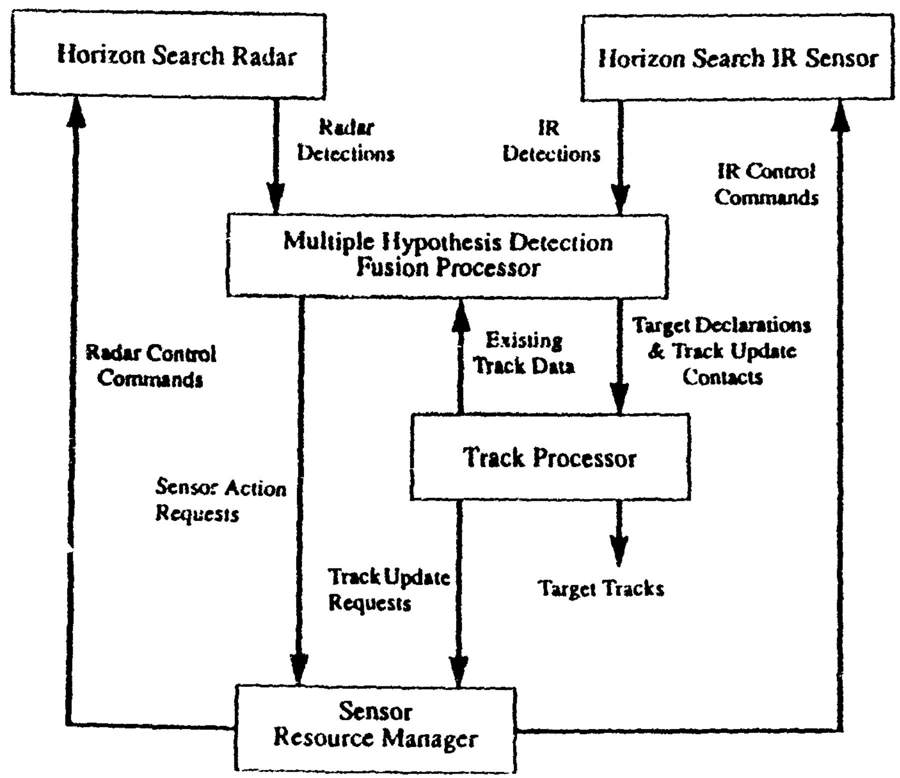
14.14

ADVANCED CONCEPTS

14.14


FAR-TERM
SYSTEM ARCH
ENGINEERING
CDS
AAW
ASUW
ASW
DETECT
CONTROL
COMMAND
ENGAGE
OBJECTIVES
PROVIDE TECH FOUNDATION FOR DEV
OF DISTRIBUTED C2 ARCH TO SUPPORT
SELF DEFENSE
ACHIEVE
SYNERGISTIC INTEGRATION OF SYSTEM
ELEMENTS
SYSTEM RESPONSIVENESS TO NEW/
INNOVATIVE THREATS
SYSTEM AFFORDABILITY
APPROACH
ARCHITECTURAL FRAMEWORK &
CAPABILITIES
SYSTEM CONCEPT(S)
DEVELOP CRITICAL C&C TECH
PERFORM SYSTEM ENGINEERING &
INTEGRATION
CONSTRUCT LABORATORY "BREADBOARD"
MODEL
SYSTEM TECHNOLOGIES
MILESTONES
DEFINE C&C REQUIREMENTS MAY 91
FUNCTIONAL ALLOCATION DEC 91
ID CRITICAL C&C TECH MAY 92
COMMENCE BREADBOARD DEV NOV 92
COMMENCE TECHNOLOGY OCT 93
ASSESSMENT
SYSTEM TECH AUG 94
ASSESSMENT

MULTI-SENSOR DETECTION SYSTEM CONCEPT FOR LOW-FLYING, LOW OBSERVABLE TARGET DETECTION



14.16

COMPELLING MOTIVATION FOR INTEGRATED IR / RADAR HORIZON SEARCH

* LOW FLYING TARGETS MOST STRESSING RADAR PROBLEM
  * CLUTTER
  * PROPAGATION
* HIGH SPEED TARGETS DRIVE RADAR SFT TO < 2 SEC
  * LIMITS PERFORMANCE OF RADAR AGAINST ALL TARGETS
  * CAN LIMIT CLUTTER REJECTION PERFORMANCE
* ABOVE 1 DEGREE IR SUFFERS LOSSES:
  * 50% SPATIAL AND TEMPORAL CLOUD OBSCURATION
  * SPATIAL SNR DEGRADATION DUE TO CLOUD CLUTTER
* HIGH RESOLUTION HORIZON SEARCH IR COMPLEMENTS RADAR
  * CAN PROVIDE CUES TO RADAR FOR FAST, HOT, TARGETS
  * LOW-ELEV. THREATS STAY BELOW 0.1 DEGREES
  * NO CLOUD CLUTTER PROBLEM BELOW 1 DEGREE ELEVATION
* DESIGN SENSORS WITH INTEGRATION GOALS IN MIND FROM OUTSET
  * TWO COMPLEMENTARY SENSORS PROPERLY INTEGRATED COULD PROVIDE BETTER PERFORMANCE TO COST RATIO THAN A SINGLE SENSOR

14.17

MSD - SENSOR REQUIREMENTS

HORIZON SEARCH RADAR

FREQUENCY BAND:	C ----> Ku
PEAK POWER:	150 ---> 200 kW
AVERAGE POWER:	10 ----> 20 kW
PW (UNCOMPRESSED):	10 ----> 50 us
RANGE RESOLUTION:	50 ft
BEAMWIDTH (AZ X EL):	1 --> 2 X 1 degrees

PHASE STEERED ANTENNA (AT LEAST IN AZ)

HIGHLY STABLE TRANSMITTER

SUBSTANTIAL WAVEFORM FLEXIBILITY

- MUST SUPPORT LONG DWELL / LONG PULSE WAVEFORMS IN RESPONSE TO CUES (~ 1 / sec ; >= 20 dB performance improvement)
- ALTERNATIVE WAVEFORMS TO RESPOND TO VARIOUS PROPAGATION ENVIRONMENTS, ECM, AND CLUTTER

HORIZON SEARCH IR SENSOR

WAVELENGTH BAND:	MWIR (2 COLOR?) LWIR (possibly)
IFOV (V X H):	0.1 X 0.2 --> 0.5 mR
TOTAL FOV (V X H):	0.5 X 360 degrees
MW NEI:	~ 10^{-15} Watts/ cm^2

AZIMUTH SCAN SENSOR (1 --> 5 Hz) WITH TDI ?

VERTICAL SCAN W/ MULTIPLE APERTURES ?

STARING SENSOR W/ MULTIPLE APERTURES ?

MECHANICAL STABILIZATION TO ~ 2 mR

ELECTRONIC STABILIZATION TO ~ 50 uR

MINIMAL SIGNAL & DATA PROCESSING

- BENIGN CLUTTER ENVIRONMENT EXPECTED
- HIGH FALSE ALARM RATE ALLOWED AS INPUT TO FUSION PROCESSOR

14.18

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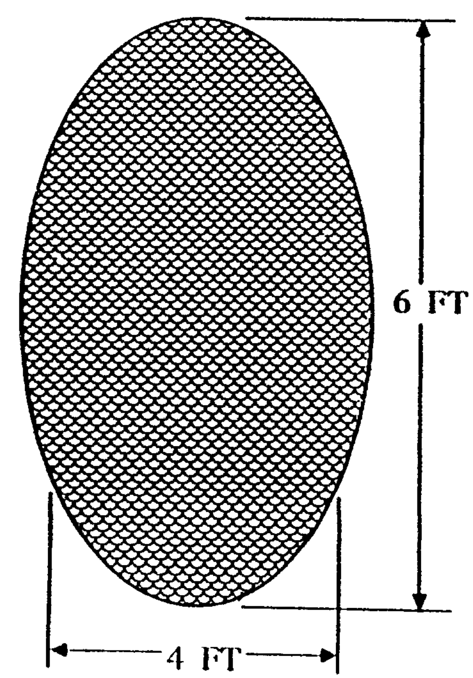
HORIZON IR SEARCH AND TRACK CONCEPTS FOR LOCAL AREA DEFENSE

SURFACE LAUNCHED WEAPONRY SEARCH AND TRACK TECHNOLOGY

MULTI FUNCTION ARRAY WEAPON CONTROL CONCEPTS



ELLIPTICAL SHAPED PLANAR PHASED ARRAY

FREQUENCY	9.0 - 10.0 GHz
NO. OF ELEMENTS	6100
BEAMWIDTHS: AZIMUTH ELEVATION	 2.0 deg 1.3 deg
GAIN	41 dB
PEAK SIDELOBES (AZ & EL)	-40 dB
POLARIZATION	HOR

14.20

EXTENDED RADAR CONCEPT

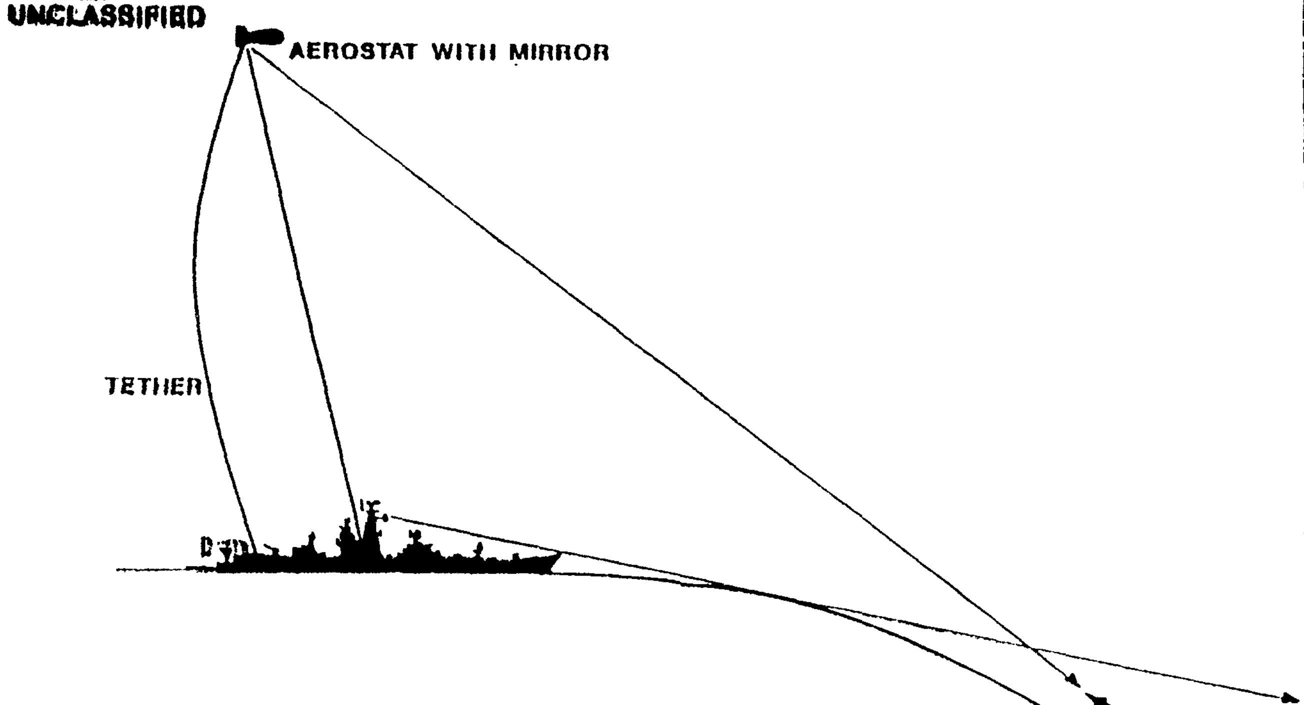
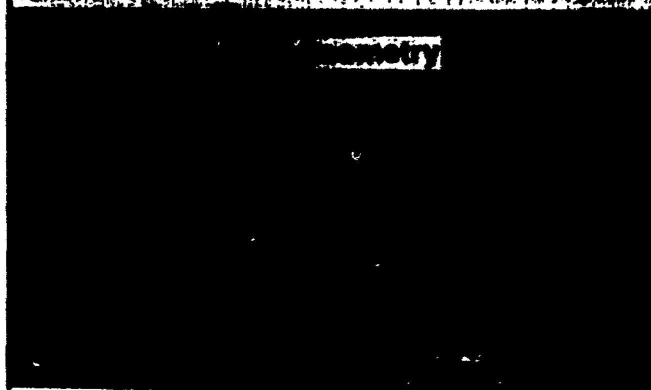


ILLUSTRATION OF A SHIP'S RADAR REFLECTING SIGNALS FROM A MIRROR CARRIED BY AN AEROSTAT OVER THE HORIZON

14.21

Tactical Wide Area Surveillance (Impulse Radar)



Operational Need

- Counter stealth
- Classification/Identification
- Low probability of intercept

Objectives

- Phenomenology
- System design
- Prototyping

Approach/Schedule/Funding

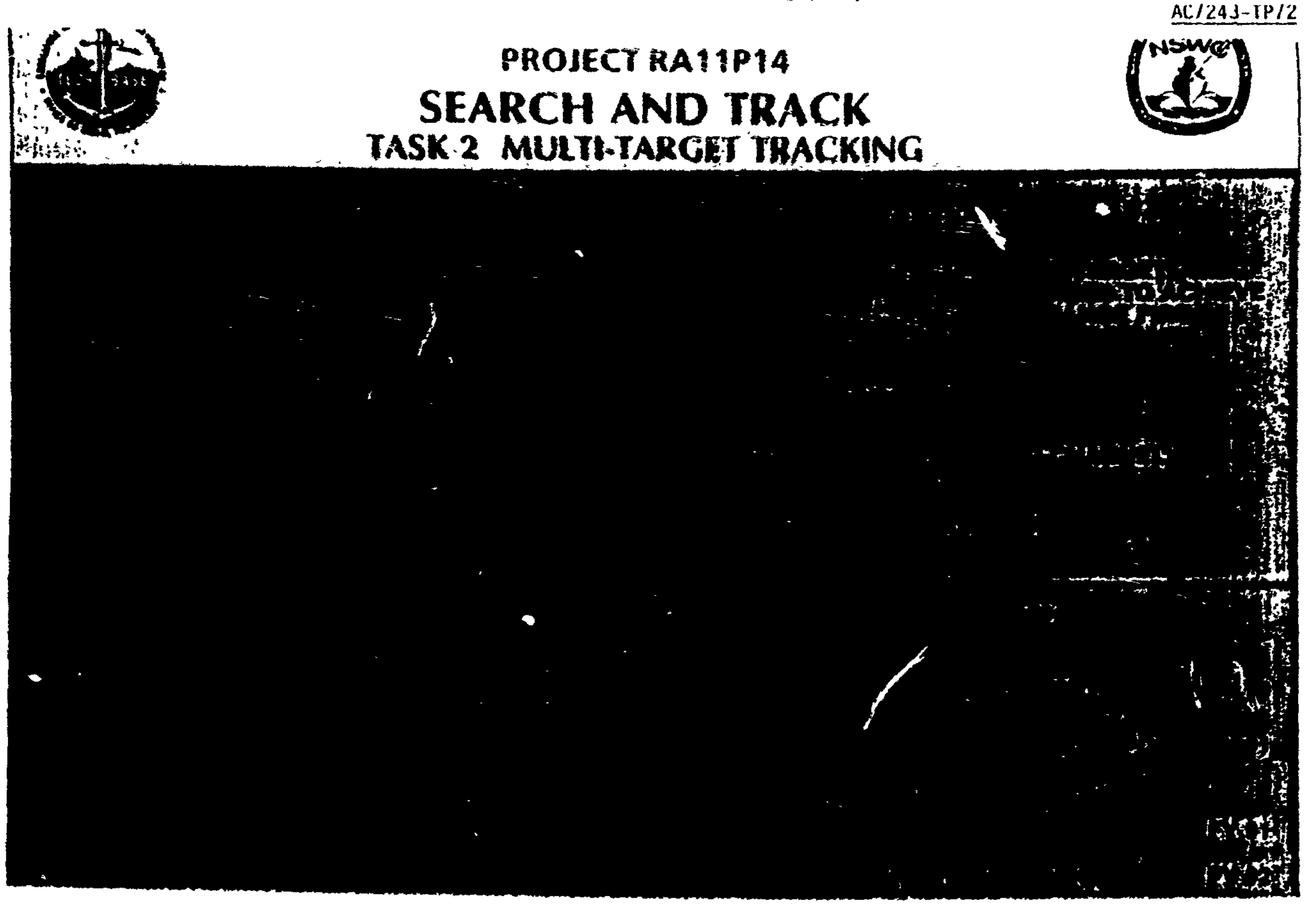
FY 90-93

- Propagation (multi-path/sea clutter dispersion)
- Power source/antenna/switch configuration
- High power testing of signal/target interaction (structure resonance)

Budget ($M)

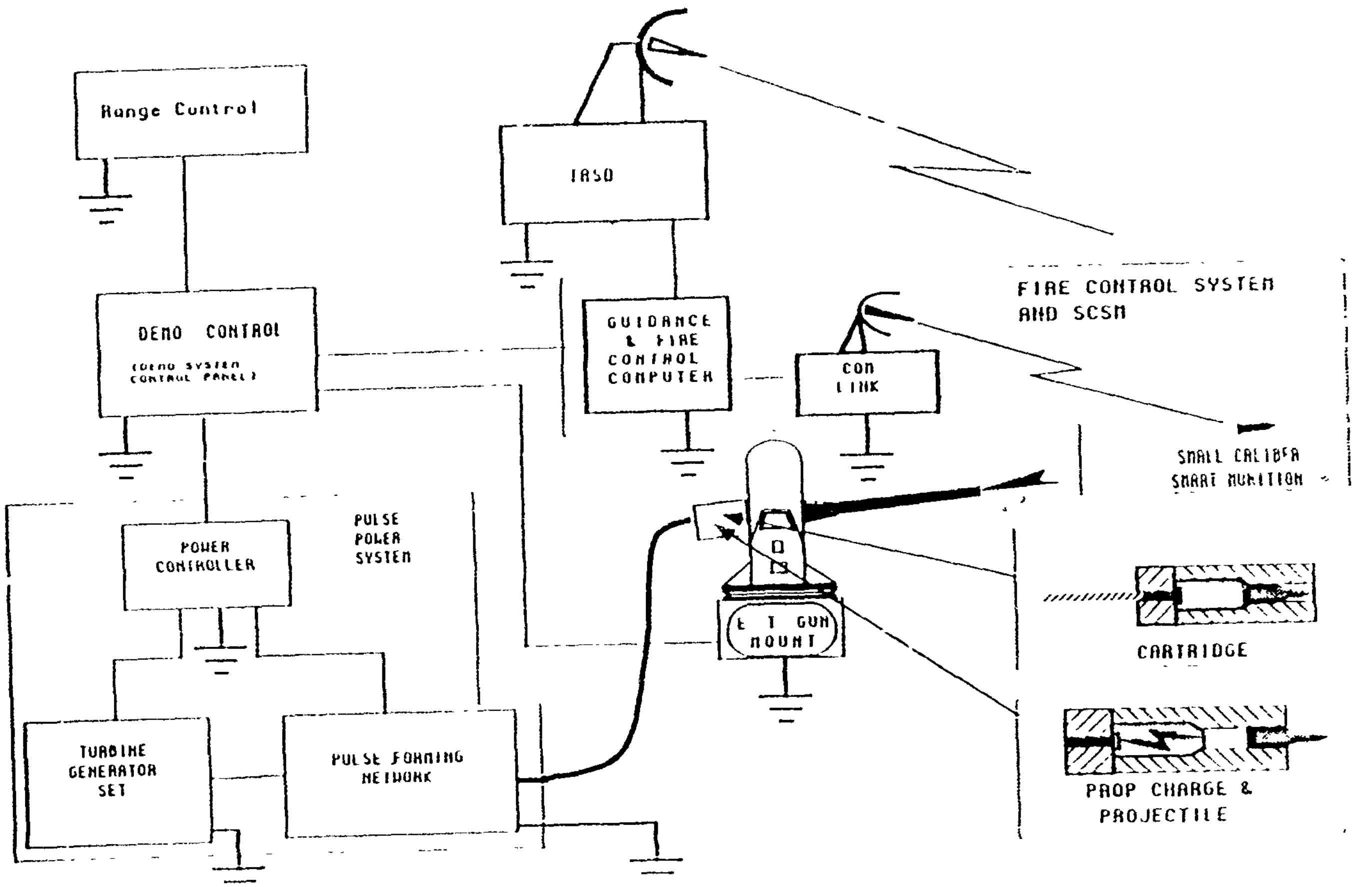
FY 90	FY 91	FY92	FY 93	FY 94
0.798	0.961	0.982	1.097	1.260

14.22


PROJECT RA11P14
SEARCH AND TRACK
TASK 2 MULTI-TARGET TRACKING
NSWC

14.24

ET DEMONSTRATION SYSTEM

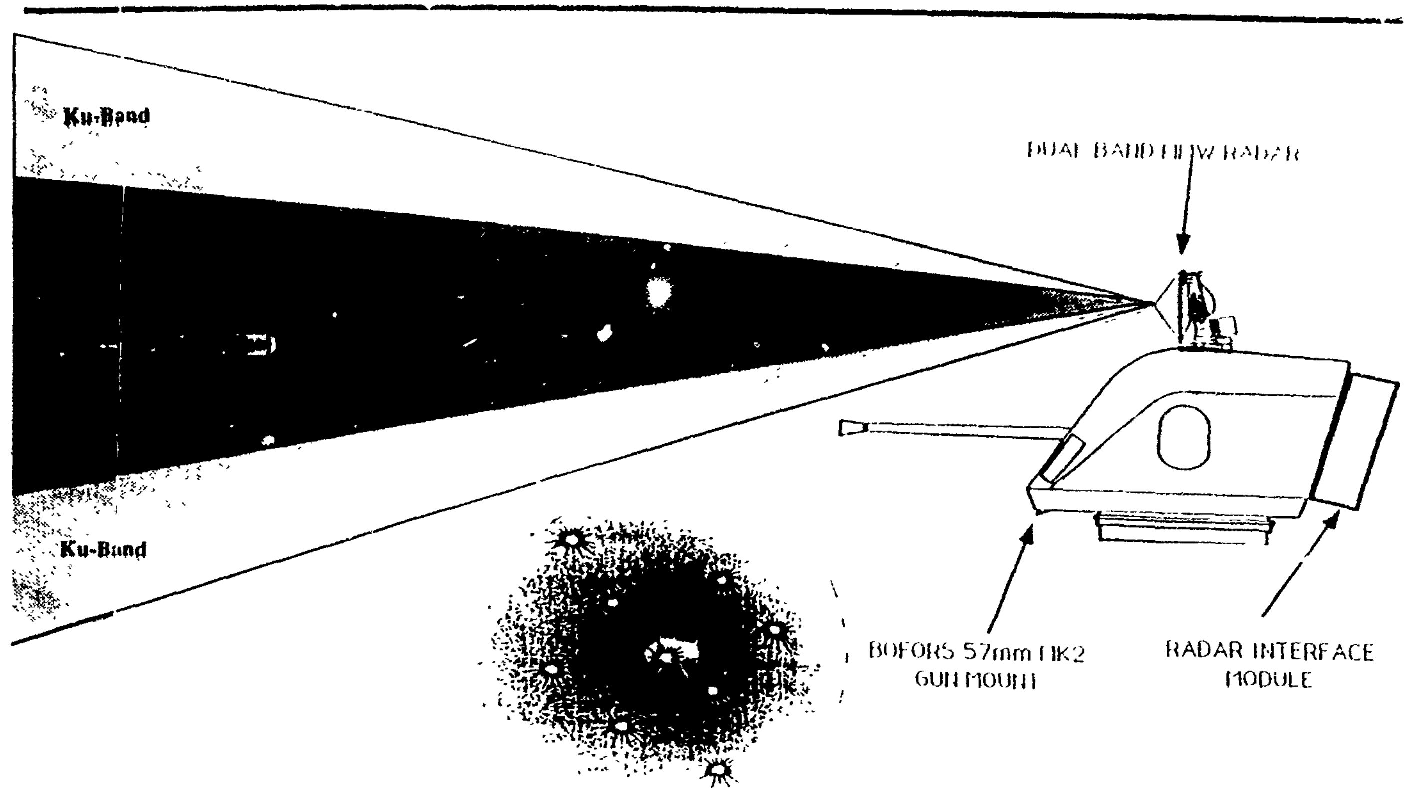


SCSM SYSTEM REQUIREMENTS

TARGET	DEMO	TACTICAL
INBOUND VELOCITY (M/S)	100 - 150	0 to > 300
MANEUVERABILITY (G's)	< 0 2	0 to > 4
ALTITUDE (M)	10 - 30	Seaskimmer to 5000
JINK ?	NO	YES
PROJECTILE		
MAX VELOCITY (KM/S)	1000	1300
MAX. MANEUVERABILITY (G's)	10	40 - 60
MAX LATERAL DELTA V (M/S)	25	0 - 500
MAX DIAMETER (MM)	40 - 60	40 - 60
KILL MECHANISM	KE (HIT-TO-KILL)	KE (HIT-TO-KILL)
MAX ACCEL /PRESS (Kgs/Kpsi)	20 / 45	30 / 67
MAX PROJECTILE LENGTH (MM)	350	350
TRACKER		
ACCURACY (MRAD)	< 0.10	< 0.10
MAX NUMBER IN AIR	1	10
MAX NUMBER OF TARGETS	1	4
MIN. TRACK RANGE (M)	500	200
TOTAL SYSTEM		
ACCURACY (MRAD)	< 0 20	< 0.20
MAX. NUMBER OF ROUNDS	1	10
MAX. NUMBER OF TARGETS	1	4
RADAR CROSS SECTION (Sq M)	0 1	< 0 1

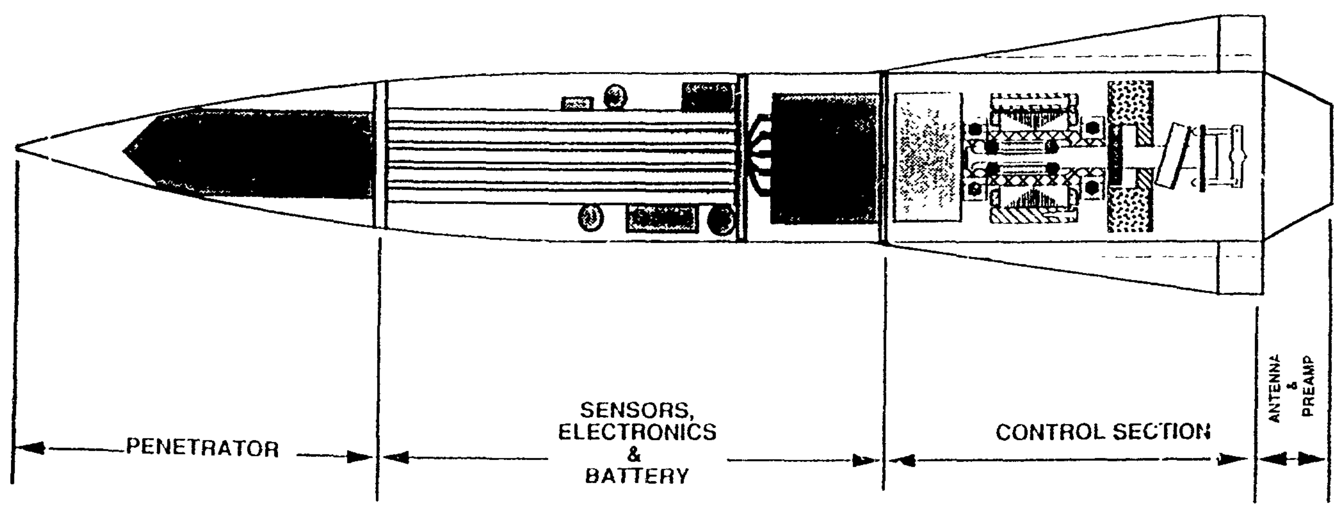
14.26

SMALL CALIBER SMART MUNITION SYSTEM CONCEPT
(CATW - COMMAND-ALL-THE-WAY)



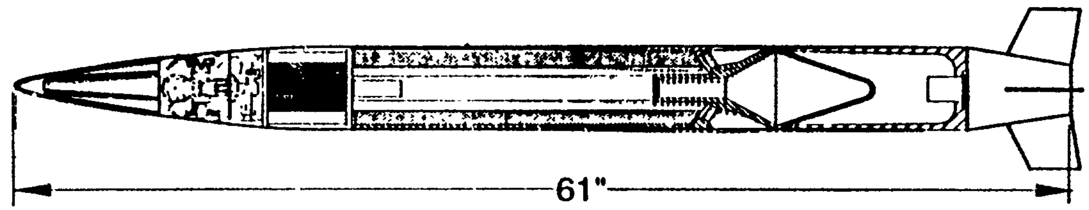
14.27

50mm Small Caliber Smart Munition Concept

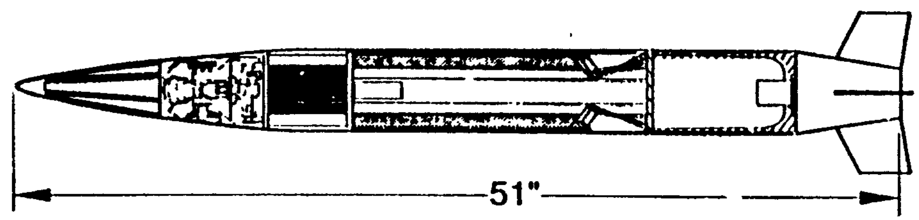


14.28

5-Inch Multi-Purpose Smart Munition Concepts



Strike & ASuW
(Double Ram)



Short Range AAW
(Single Ram)

Guidance: Command-All-The-Way and/or IR

Strike & ASuW Range: 2-100 km

Short Range AAW Range: 1-10 km

14.29

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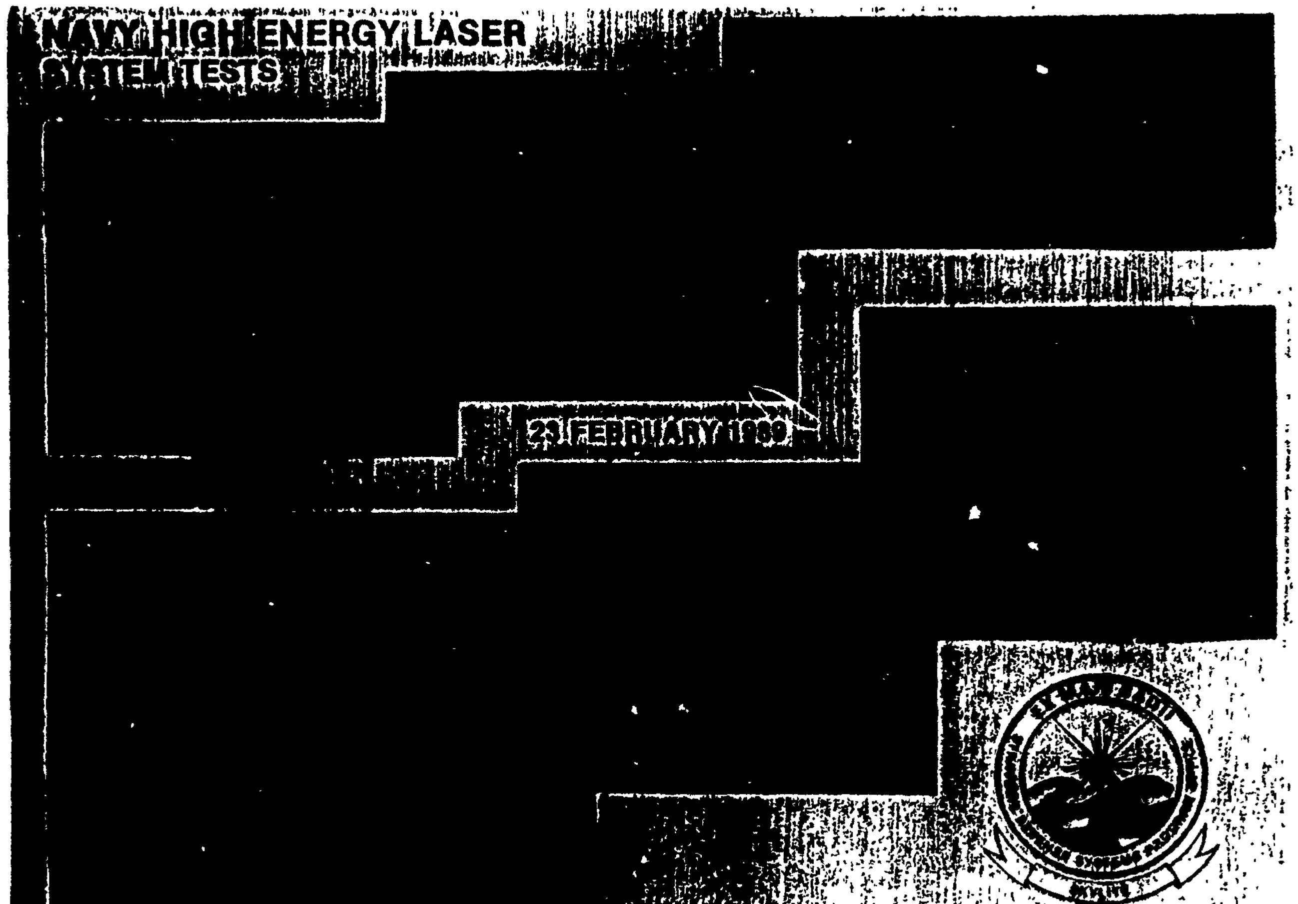

NATO UNCLASSIFIED

DIRECTIONS FOR POINT DEFENSE TECHNOLOGY

- REQUIREMENTS FOR STAND-ALONE SYSTEMS
  - MODULAR COMPONENTS
- ADVANCED WEAPON CONCEPTS ESSENTIAL
  - DEW
  - HYPERVELOCITY GUNS WITH GUIDED PROJECTILES
  - MISSILES WITH COMMAND GUIDANCE
- KILL ASSESSMENT FOR SOFT KILL & EW
- LPI
- SENSOR, WEAPON, EW INTEGRATION
- EXTENDED RANGE DETECTION WITH ORGANIC ASSETS

14.31

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14. Abstract: This presentation defines the functional integration of the Rolling Airframe Missile (RAM) Guided Missile Weapon System and Phalanx Close in Weapon System (CIWS) into a Self Defence System for multiple ship classes. The RAM is a lightweight, quick-reaction, high firepower weapon system which provides anti-ship missile (ASM) defence. It is a joint development by the US and German Navies and is currently in limited production. The Phalanx CIWS Block I is a high fire rate automatic target acquisition and gun fire control system that provides a hard kill defence against surviving ASMs. The link that allows Phalanx to provide designations to RAM is called the RAM Interface Unit (RIU). The RIU incorporates the US Navy standard AN/UYK-44 computer, input/output ports, and software which provides a common interface for a given ship and its combat systems.

RAM/Phalanx Integrated Self Defense Weapon System (NU)

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Abstract
RAM/Phalanx Integrated Self Defense Weapon System (NU)

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(714-945-6764)

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(NU) This presentation defines the functional integration of the Rolling Airframe Missile (RAM) Guided Missile Weapon System and Phalanx Close in Weapon System (CIWS) into a Self Defense System for multiple ship classes. The RAM is a lightweight, quick-reaction, high firepower weapon system which provides anti-ship missile (ASM) defense. It is a joint development by the US and German Navies and is currently in limited production. The Phalanx CIWS Block I is a high fire rate automatic target acquisition and gun fire control system that provides a hard kill defense against surviving ASMs. The Phalanx is currently installed or planned to be installed on over 330 US Navy ships. The link that will allow Phalanx to provide designations to RAM is called the RAM Interface Unit (RIU). The RIU will incorporate the US Navy standard AN/UYK-44 computer, input/output ports, and software which provides a common interface for a given ship and its combat system. The operator will be provided a tactical monitor, driven by the RIU, which can provide insights into the RAM and Phalanx engagement status for improved short range battle management. The RAM/CIWS self defense system can be interfaced to a ship's combat system as a modular unit providing increased range and firepower for layered self defense against the ASM threats. The FFG-7 ship class is studied as the first potential application of this capability. This capability is ideally suited for the ASM defense of small ships where space is at a premium and cost is a major driver. This effort is currently an industry initiative in the demonstration phase.

(NU) The top level results of this study, including the recommended functional integration approach and the operational benefit of this integrated self defense system versus ASM scenarios are presented.

(NU) The study found that the integration of the RAM and Phalanx CIWS systems is feasible, using the FFG-7 ship class as the first application. Adding RAM to the FFG-7 class ship, in either of its stand alone launchers, provides a strong additional anti-ship missile defensive layer. Additionally, integrating RAM and Phalanx provides strong casualty backup for existing ship combat systems and helps reduce potential ship damage from high speed debris. The combinations of the two systems significantly enhances ship surviveability in low and high intensity conflicts.

1.0 INTRODUCTION (NU).

(NU) General Dynamics performed an integrated RAM/CIWS Proof of Principle Demonstration in May, 1988. This demonstration was performed at sea aboard the USS David R. Ray (DD-971) using a CIWS Block 0 fire unit and the RAM launching system test installation. The successful results from this demonstration supported a top level design concept study to investigate the operational performance benefit of RAM/CIWS integration aboard ship and to determine feasible engineering approaches. Figure 1.0-1 describes the integration tasks studied. This report represents the RAM/CIWS FFG-7 concept of application and operational performance benefits developed under the study.

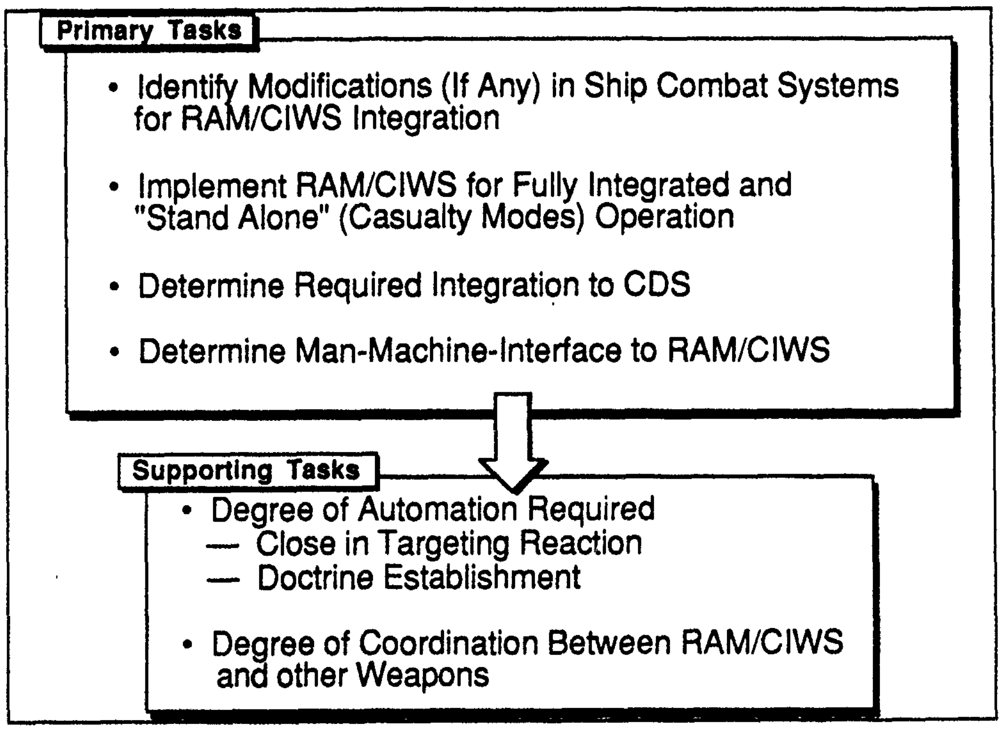

Figure 1.0-1. RAM/CIWS Integration Study Tasks (NU).

(NU) The FFG-7 class was studied as the initial ship class for integration concepts for this increased self defense capability. The study assumes the FFG-61 Combat System Update as the

baseline system configuration for FFG-7 system design concepts and considers the CIWS Block 1R3 configuration as the baseline for the RAM/CIWS integration. The study ground rules (NU) included the requirement to integrate with existing ship combat systems without causing increased operator or computational burden. The study assumed that no major combat system or fire control radar computer upgrades (i.e. AN/UYK-7 to AN/UYK-43) would be required for system implementation. Additionally, only existing ship sensors were to be utilized. In development of the specific FFG-7 design concepts, the study pursues RAM/CIWS integration concepts which support common interfaces for potential RAM/CIWS implementation in other ship classes. Such integration must be achievable without functional modification of either RAM or CIWS and is assumed to be implemented within the existing and planned performance improvements of the two systems.

(NU) General Dynamics Valley Systems Division and Pomona Division in conjunction with QuesTech Inc., San Diego performed this study under Contract No. 605151-L for the Applied Physics Laboratory of the Johns Hopkins University, Laurel, Maryland. The full study report is obtainable through the Commander, Naval Sea Systems Command, Attn: PMS-420, Washington D. C. 20362-5101; (703-692-7293).

2.0 RAM/PHALANX INTEGRATION STUDY SUMMARY (NU).

(NU) This section provides a brief summary of the RAM/Phalanx concept of application and the ship configurations studied for the FFG-7 class of ships.

2.1 RAM/CIWS Concepts of Application Summary(NU).

(NU) This study develops short range anti-air warfare (SRAAW) concepts of application for the operation of an integrated RAM/CIWS self defense system aboard ship. The study analyses were coordinated with the Fleet Combat Direction System Support Activity (FCDSSA), Dam Neck, Va for the combat system integration requirements on the FFG-7; the Surface Warfare Development Group (SWDG), Norfolk Va for tactical employment and operator interface recommendations; and the MK-92 engineering staff at the Naval Surface Weapons System Engineering Station (NSWSES), Pt. Hueneme, Ca for feasibility of the MK-92 fire control system and RAM/CIWS integration approach.

(NU) The overall integrated RAM/CIWS concept of application derived from these interface meetings is depicted in Figure 2.1-1. Aboard ship, the combat direction system (CDS) is the key area for the management and implementation of the ship's primary mission. Since SRAAW self protection is not a primary mission of the ship, the proposed system implementation of the integrated RAM and Phalanx systems assumes that the processing for close in target engagements should be done in a RAM Interface Unit (RIU) outside the CDS processing, relieving the CDS of any additional computational burden and primary mission impact. This implementation also allows for "stand alone" RAM/CIWS operation if the primary ship radars or CDS are lost due to down equipment or casualty modes. However, the RIU should also be interfaced to the CDS to benefit from the target tracks established within the ship's major combat systems.

(NU) The primary concept of application assumes that all target tracks established by the ship CDS should be provided via a standard NTDS input to the RIU, an AN/UYK-44 computer, which then filters the target tracks for any target penetrating the SRAAW engagement boundary. In this

case, where it is integrated with the CDS, the RIU will then correlate radar tracks received from the CIWS to the CDS provided tracks, associate SLQ-32 information required for RAM engagements, (NU) and provide the close in weapons assignment of the RAM missiles for the ASM engagements. Current ground rules assume the CIWS engages any surviving targets with no functional changes to the CIWS being driven by the RAM and Phalanx integration.

(NU) The RIU integration with CDS is the recommended primary approach and is utilized when the ship is a combatant with all of its combat systems and sensors in operation. However, stand alone RAM/CIWS operation is provided when full ship capability is not available. In these cases, the CIWS supplies the SRAAW radar tracks to the RIU instead of the CDS. This situation arises when the ship's primary radars are down or are heavily jammed or in the case of small RCS targets where the only target detections may come from the CIWS. SLQ-32 data is assumed available to the RIU either through a CDS link or through a direct connection port provided on the RIU's AN/UYK-44.

(NU) Man-Machine-Interface (MMI) requirements drove use of a small standard tactical monitor allowing display of RAM and CIWS system status and weapon engagements. This Self Defense Control Monitor is depicted in Figure 2.1-1 and allows flexible installation in the limited space areas in the Combat Information Center (CIC) of the FFG-7. This approach also supports MMI on numerous ship classes, including those non-NTDS ships without extensive CICs.

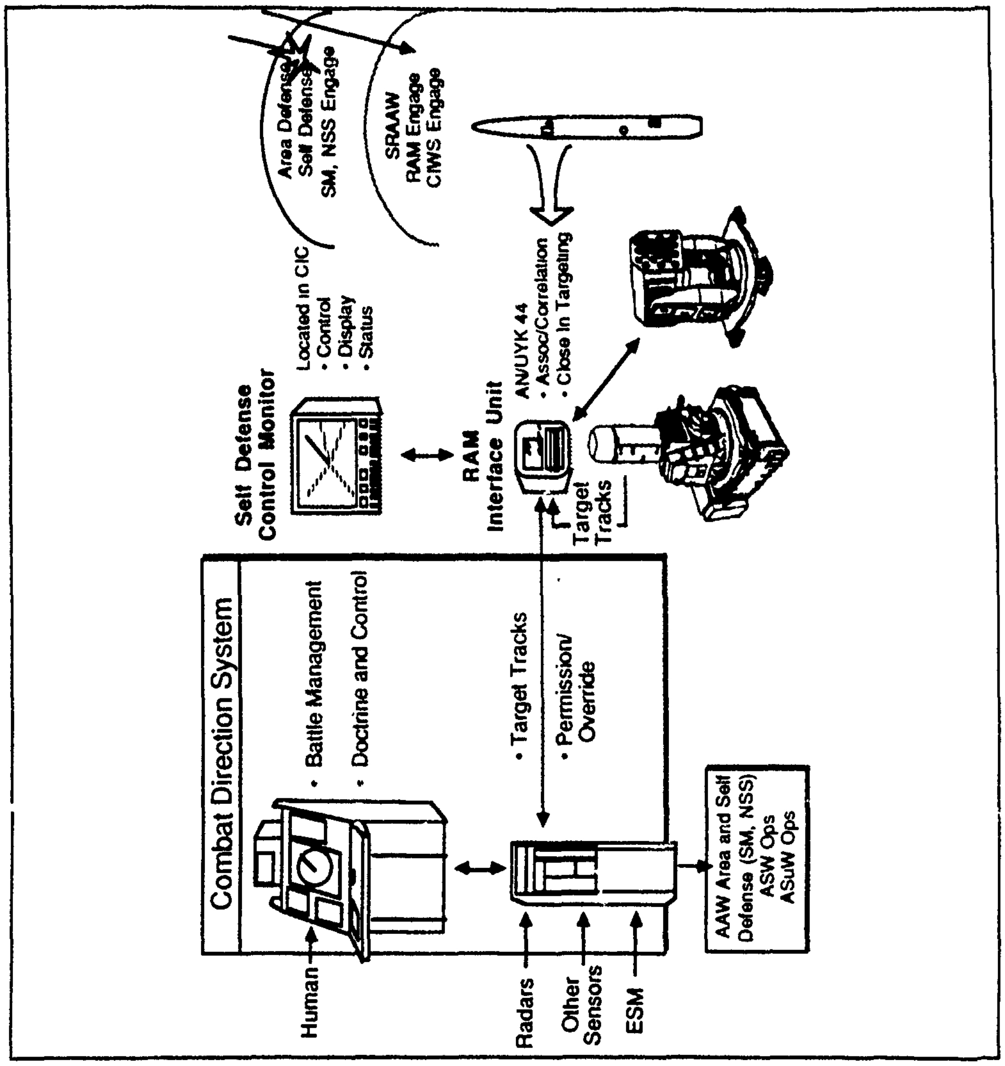

Figure 2.1-1. RAM/CIWS Allows Both Integrated and Stand Alone Operations (NU).

2.2 RAM/CIWS Proposed FFG-7 Ship Configurations (NU).

(NU) The study includes three RAM/CIWS configurations for the FFG-7 class ship (Figure 2.2-1). The first configuration assumes that RAM is integrated into the MK-13 launcher. This configuration requires a two RAM on a strongback design that fits interchangeably with Standard Missiles (SM) within the MK-13 launcher magazine. This strongback's pre-design was provided by the Northern Ordnance Division of the FMC Corporation, Minneapolis, Min. The study assumes that 10 strongbacks representing a 20 RAM operational loadout could be carried and still retain up to 6 Harpoons , 23 SM, and a test round in the magazine. This configuration requires added integration complexity for the RIU since launcher control must now be given to the RIU prior to RAM engagements. Additionally, the RAM engagement time lines are driven by loading, restowing (or jettison), and reloading of the RAM strongbacks. These time line inputs were evaluated as part of this configuration's operational performance benefit analysis. Under this configuration, the weight and balance impact of integrating RAM aboard the FFG-7 is negligible, but the rapid fire rate of RAM is limited to 2 rounds before the strongback cycle time is required. RAM engagement coverage is driven by MK-13 limits.

(NU) RAM in the production 21 round MK-49 launcher configured on the 02 level replacing the MK-75 76mm gun is the second FFG-7 configuration evaluated. (Due to limited space and critical weight and balance issues on the baseline FFG-7, MK-49 installation options are limited if existing ship equipment is not removed). This configuration supports rapid RAM engagement timelines but raises the FFG-7 vertical center of gravity (VCG) from approximately 18.50 ft to 18.54 ft (including equiment and a 21 round magazine on the 01 level). Both the RAM in MK-13 and RAM in MK-49 launcher configurations are limited in their RAM/CIWS overlapping engagement coverage since the respective systems are not near each other on the ship.

(NU) The third FFG-7 configuration considered RAM installed in two 10 round RAM Alternate Launcher Systems (RALS) port/starboard on the 02 level providing over 360° of ASMD coverage and providing the best RAM/CIWS radar overlap due to the aft installation of CIWS. The RALS system is a commercial development by General Dynamics, Per Udsen, a Danish company, and RAMSYS GmbH, a German industry joint venture established to produce the RAM missile. This configuration provides 10 rounds for engagements on each side of the ship but also raises the ship's VCG to approximately 18.58 ft (including equipment and a 21 round magazine located on the second deck).

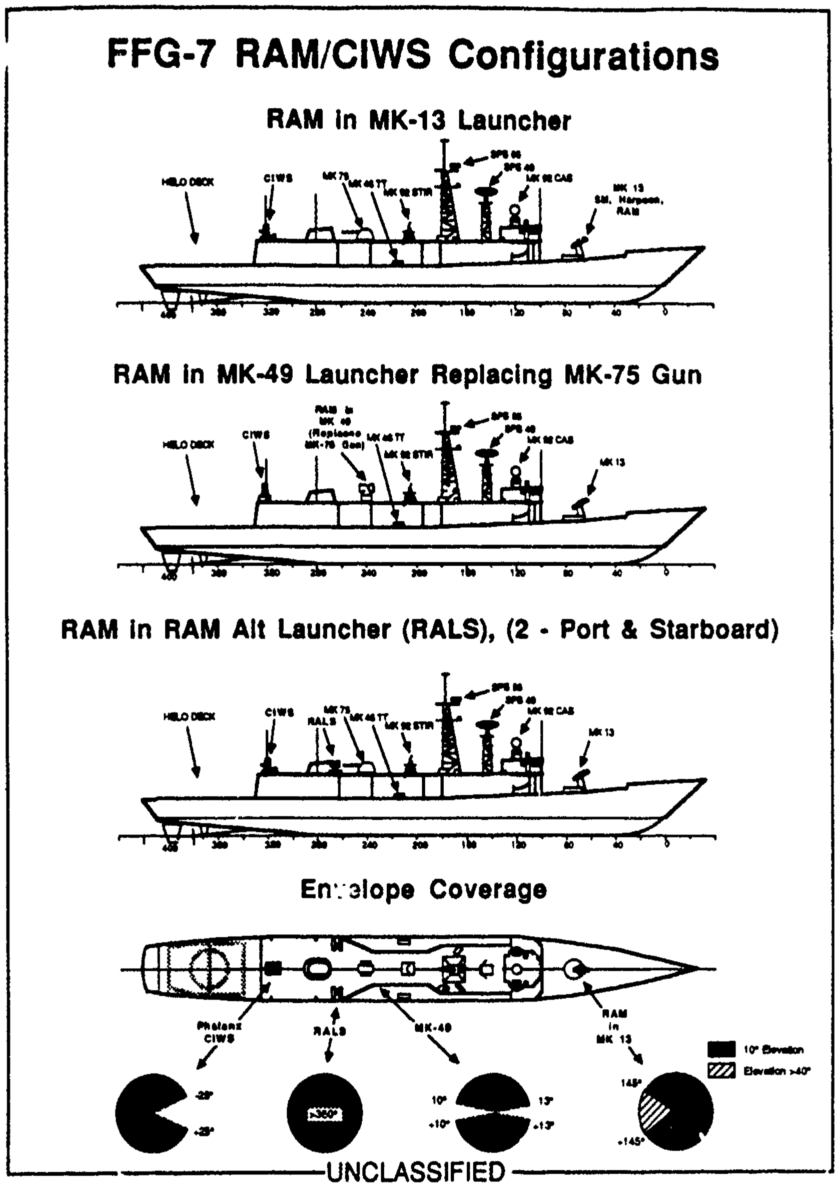

Figure 2.2-1. FFG-7 Integrated RAM /CIWS Ship Configurations (NU).

3.0 CONCEPT OF SELF DEFENSE FUNCTIONAL INTEGRATION (NU).

(NU) This section covers the functional integration of the combined RAM and Phalanx systems with existing ship systems. An overview of the RAM and CIWS systems is first given. An overview of the functional blocks that make up the integrated self defense weapon system and the ship systems that are necessary to provide data and control is discussed next.

3.1 RAM Guided Missile Launching System Description (NU).

(NU) The RAM MK-31Guided Missile Weapon System (GMWS) consists of the 21 cell MK-49 Guided Missile Launching System (GMLS) and the MK-44 Guided Missile Round Pack (GMRP) (missile enclosed in cannister). Additionally, a RAM Alternate Launching System (RALS) utilizing a lightweight 10 cell launcher is under commercial development by a joint venture of United States, German, and Danish companies. The RALS uses the same basic GMLS support equipment developed for the MK-49 system. The RAM equipment is shown in Figure 3.1-1.

(NU) RAM's employment is shown in Figure 3.1-2. The current (Block 0) RAM missile is effective against targets with active emitters. The missile's Radio Frequency (RF) receiver provides the initial target acquisition with a broad angle coverage that allows for launcher-pointing error or ship sensor designation error. This broad angle coverage also provides a "shoot around the corner" capability for the RAM system. Transition to the highly accurate Infrared (IR) guidance is automatic when the IR target signal criterion are satisfied. RAM also has the capability to fly in RF mode All-The-Way to intercept in bad weather or against targets with very low IR signatures. The Block 1 upgrade to the RAM is planned as an IR Mode Upgrade (IRMU) seeker, allowing IR Only capability for missile launch and in-flight aquisition on targets without active emitters. The IRMU seeker is currently in concept development by the US and FRG navies.

(NU) In order for RAM to properly engage targets, it requires operation of on board ship sensors for target detection and an external designation source (EDS) computer to perform the target designation and engagment control functions. The current US sensor suite for RAM is the Target Acquisition System (TAS) MK-23 Radar, and the AN/SLQ-32 ESM set. Either one of these sensors can initiate a RAM engagement. The RAM GMWS concept is designed for automatic target detection, association of the dissimilar sensor data, and the automatic launch of missiles providing a quick-reaction, self defense system. Flexibility within the system also allows semi-automatic or manual operation. The GMLS is composed of four subsystems controlled by microprocessors and a servo-driven 21 cell (MK-144) or 10 cell launcher mount.

(NU) The RAM GMLS requires an external target designation source (EDS). This EDS could be the ship's CDS computers, a primary fire control radar computer (such as the MK-23 TAS), or an AN/UYK-44 based RAM Interface Unit (RIU). The ship's EDS communicates with the RAM GMLS through a digital data link. This interface is implemented in general accordance with MIL-STD-1397A for a Naval Tactical Data System (NTDS) parallel configuration. The NTDS link with RAM can be chosen as types A, B, or C, providing high flexibility in ship installation.

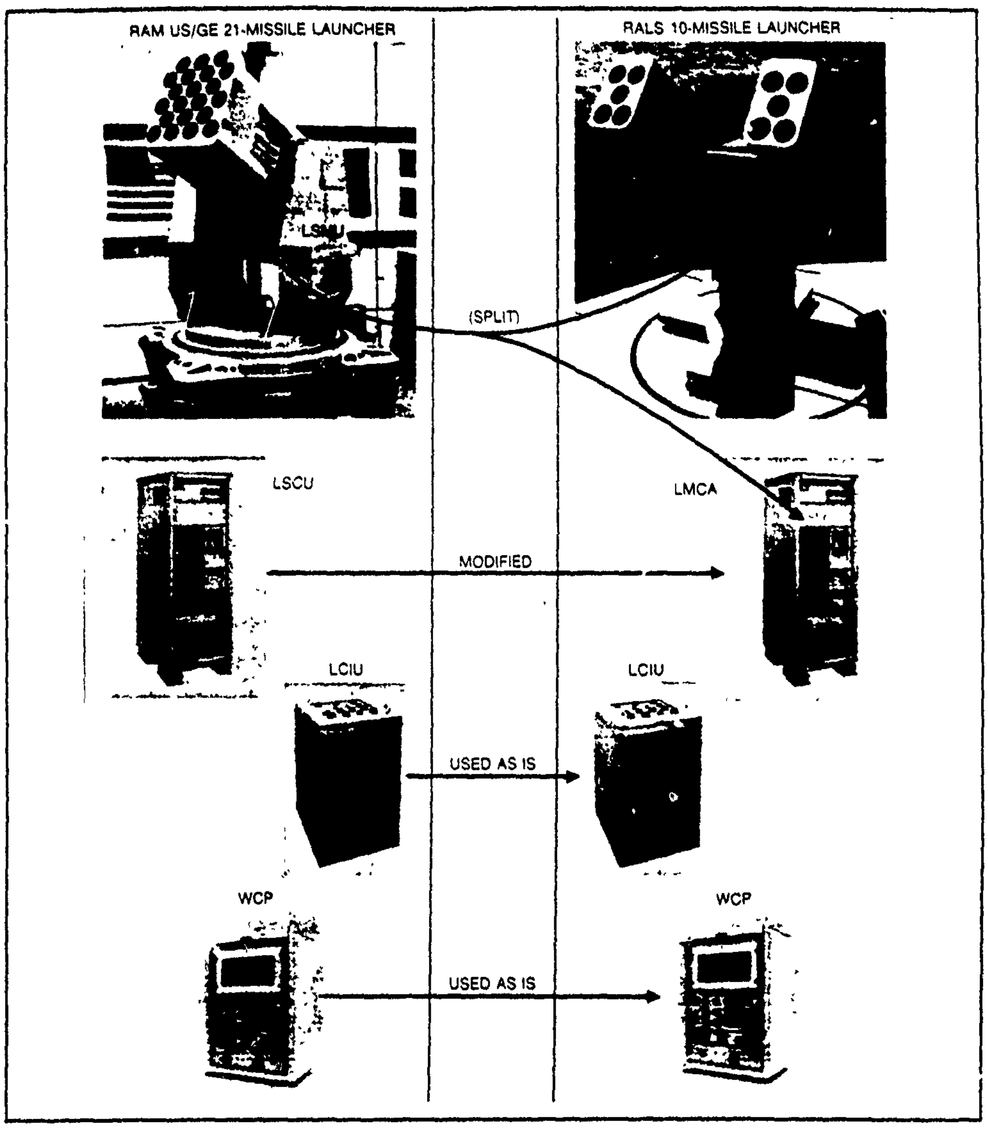

Figure 3.1-1. RAM MK-49 and RALS Equipment (NU).

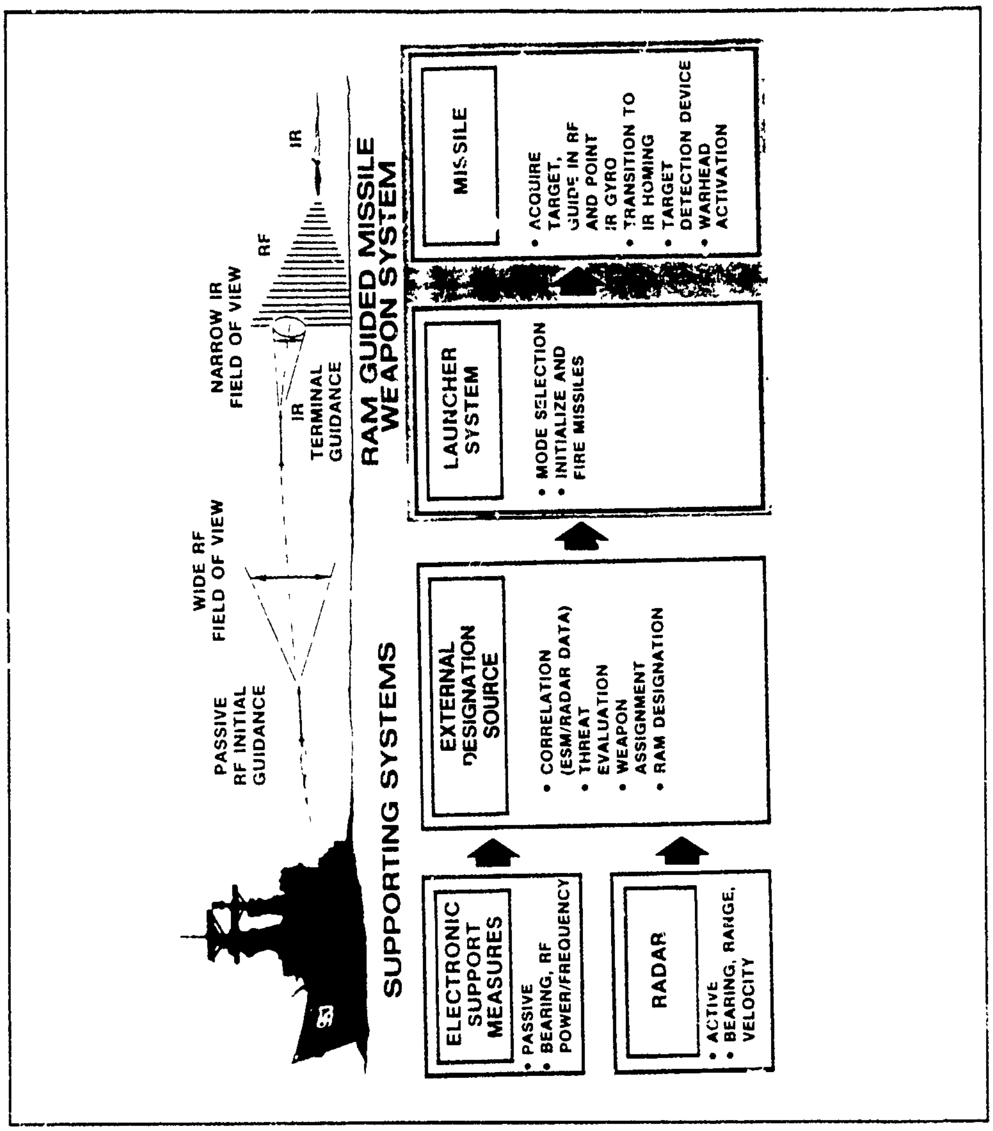

Figure 3.1-2. RAM Operational Concept (NU).

(NU) The uniquely flexible RAM GMWS can engage a target using radar data, ESM data, or a combination of both. Once the Block 1 IRMU seeker RAM is fielded, the RAM will also be capable of engaging (in IR Only mode) a non-radiating target using track data from an Infra-red Search and Track Set (IRST), a Forward Looking IR (FLIR) sensor, or a radar. The EDS should perform the following functions for the RAM GMWS: Threat Evaluation, Prioritization, Threat Engageability, Engagement Queuing, Weapon Selection, Weapon Assignment/Designation, Engagement Monitoring, and Survive Assessment.

3.2 Phalanx Close In weapon System Description (NU).

(NU) The Phalanx CIWS is a fast reaction, high fire rate, computer controlled radar and 20 mm gun system designed to engage ASM, fixed wing aircraft, or surface targets at short range Phalanx is designed as a unitized modular system suitable for installation on most classes of surface ships. The Phalanx is a total weapon system that encompasses functions usually performed by separate, independent weapon systems. It provides autonomous search, detection, declaration (threat evaluation), acquisition, track, firing, automatic kill assessment, and cease fire. The Phalanx MK-15 CIWS is comprised of the components shown in Figure 3.2-1

(NU) The Phalanx uses closed loop projectile spotting to provide an increased hit capability over open loop systems. The weapon system radar simultaneously measures both target location and projectile stream location at the target and updates the fire control solution to reduce any difference to zero. In this way, Phalanx automatically and continuously directs a stream of projectiles onto the target throughout the firing period. The Phalanx weapon group contains a coherent pulse doppler radar having separate stabilized search and track antennas and a shared transmitter, receiver, and signal processor. The gun mount is stabilized and computer directed. The weapon group contains the general purpose computer and environmental control equipment.

(NU) The Block I upgrade for Phalanx provides for increased elevation search, a fire rate increase from 3000 to 4500 shots per minute, a magazine increase from 980 to 1550 rounds, and major pulse doppler radar improvements. These radar upgrades provide much improved detection capability against small radar cross section targets. Additionally, a reliability improvement program is in place raising MTBF specification from 136 to 350 hours.

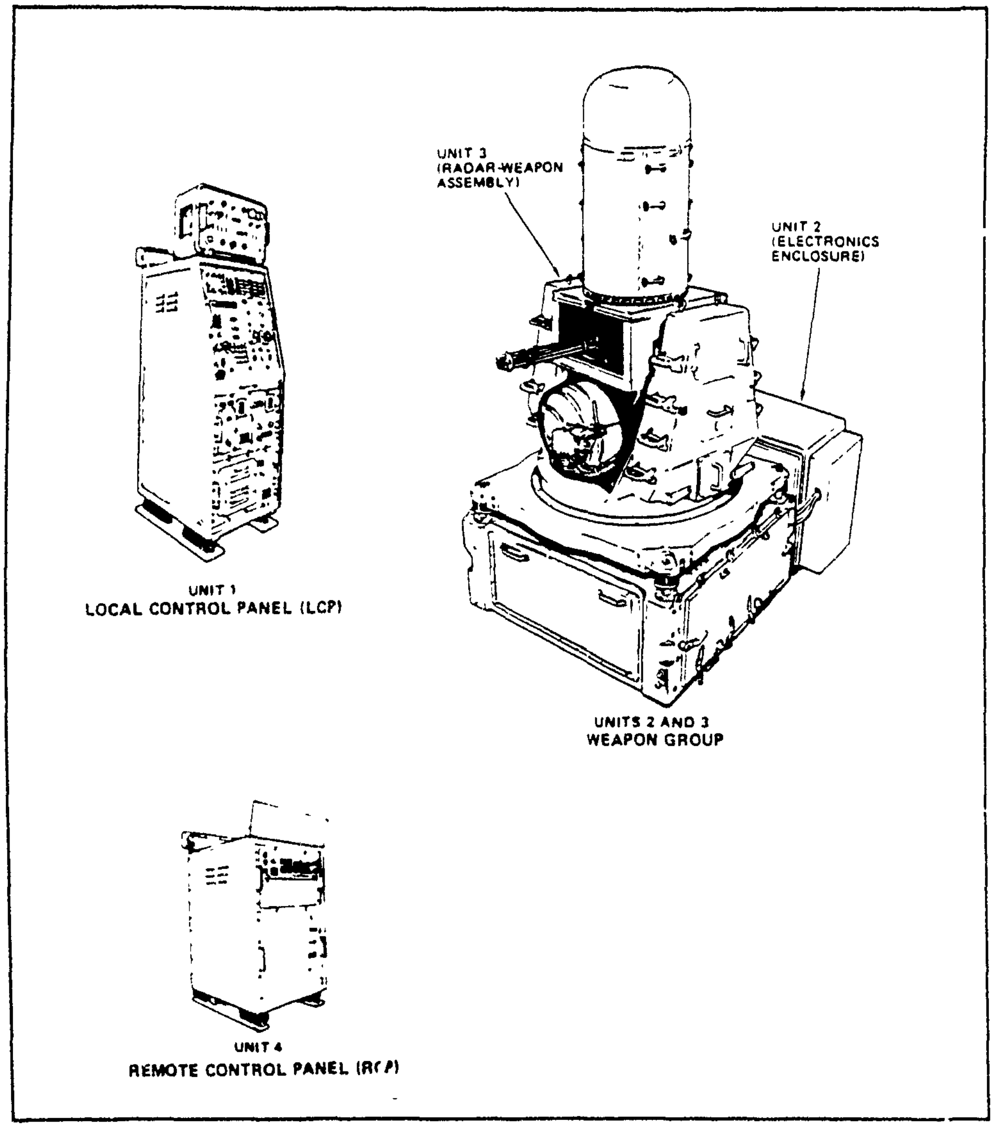

Figure 3.2-1. Phalanx CIWS Block I Equipment (NU).

3.3 Overview of the RAM/Phalanx System (NU).

(NU) Figure 3.3-1 shows the major blocks that generally make up the integrated RAM/Phalanx system and its generic combat system interface with the ship.

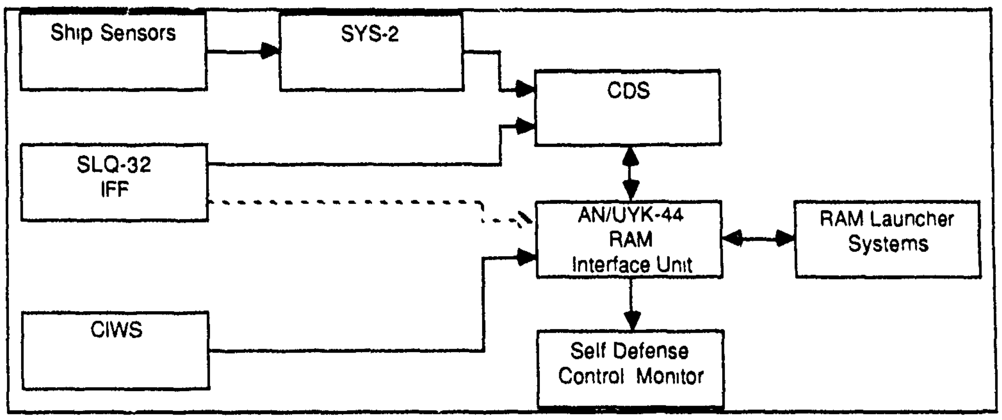

Figure 3.3-1. Self Defense Weapon System Overview (NU).

(NU) The sensors for the CDS consist of the ship's air search and fire control radars and the SLQ-32 passive receiver. The ship radar sensors detect targets and provide the range, range rate, and bearing for each of the threats detected. The individual radar tracks are correlated in a system such as the SYS-2 system to develop a composite set of tracks on targets in the area. These tracks are passed from the ship's CDS to the RIU. Because the RAM system is a passive radio frequency homing missile, the SLQ-32 data is very important to the operation of the self defense system. The SLQ-32 tracks must either be passed through the ship's CDS to the RIU or have a direct connection to the RIU.

(NU) The CIWS radar system provides target tracks directly to the RIU It measures the target's range, bearing, and coarse elevation and derives range and angle rates. By integrating CIWS directly with the RIU, the self defense system can still function and launch RAM missiles even if the ship's radars and/or CDS is down.

(NU) The heart of the integrated RAM/CIWS system is the RIU. The RIU functions as the external designation source for RAM in this system. There are four primary functions which the RIU performs in addition to the housekeeping of the computer and input/output control. The first function is to correlate and associate the tracks from the various sensors making a composite track file of the detected threats. The RIU correlates the track data from CIWS and the SYS-2 or CDS output of the ship radars to develop a composite track list of all radar tracks in the area. It then associates the SLQ-32 data with this track list. The SLQ-32 tracks are not merged with the radar

(NU) data due to the differences in data measured and the accuracy of the measurements. The track list contains a list of radar tracks and SLQ-32 tracks and indicates which tracks are associated with each other giving a track list having one entry per threat in the list. The second function performed by the RIU is the evaluation or a prioritization of the tracks in the track list to determine the relative priority of each threat. Each track in the track list is ranked to determine the order in which they should be engaged. This is done based upon the range and range rate of the track to determine the time until that track impacts the ship, the type of threat, the track quality or number of detects on the threat, and whether or not SLQ-32 has detected the threat. The next function is the assignment of the highest priority track to the RAM weapon system. This function takes care of all the data transfer to and from the launching system to fire the missile and engage the threat represented by the track. It also processes the status of the launcher. The last major function of the RIU is the man machine interface. The RIU provides the status of the RAM and Phalanx systems, recommends designation of a target to RAM, and responds to the controls of the operator.

3.3.1 Integration with CDS on FFG-7 Class Ships (NU)

(NU) Figure 3.3.1-1 shows the specific data flow of the ship radar data through CDS and into the weapon control processors on a FFG-7 class of ship. The radars providing the air search target data are the MK-92 CAS search radar and the SPS-49 long range air surveillance radar. The data from both of these radar systems feed into the SYS-2 Integrated Automatic Detector and Tracker system (IADT). The SPS-55 also feeds into the SYS-2 system, but this radar is a surface search and navigation radar which will probably not provide any ASM detects for the self defense system. The IADT correlates the radar data from the individual radars merging duplicate tracks of the same target into a single track. The tracks from the SYS-2 are routed both to the FFG-7 CDS Weapon Support Processor (WSP) and the MK-92 Weapon Control Processor (WCP) where they are displayed on consoles for the operators. Passive tracks from the SLQ 32 are displayed on the Electronic Warfare Operator's (EWO) console. If the SLQ-32 is in automatic mode, the top two tracks are transferred to the WSP where they can be displayed on any of the CIC display consoles. The WSP also passes these tracks to the WCP where the MK-92 Weapon Control Console (WCC) operators can engage the targets. In the manual mode, the EWO can select up to two tracks to be transferred to the WSP and subsequently to the WCP. In either mode, only bearing and ID of a maximum of two tracks are passed to the WSP and WCP. The WCC operators control the CAS and STIR tracking radars to engage targets with Standard Missile, Harpoon, and Gun Systems.

(NU) The optimum place to integrate the RIU into the ship command and control is at the WSP. However, there are no extra interfaces on the WSP AN/UYK-43 computer allowing outputs to the RIU. The next best place to interface into the ship system is at the WCP. This computer also has direct access to the SYS-2 correlated tracks and can handle up to 128 tracks. After discussions with the MK-92 technical design agents at NSWSES, this RIU to WCP interface is both feasible and the recommended approach in order to alleviate any additional computational burdem to the WCP AN/UYK-7 computer.

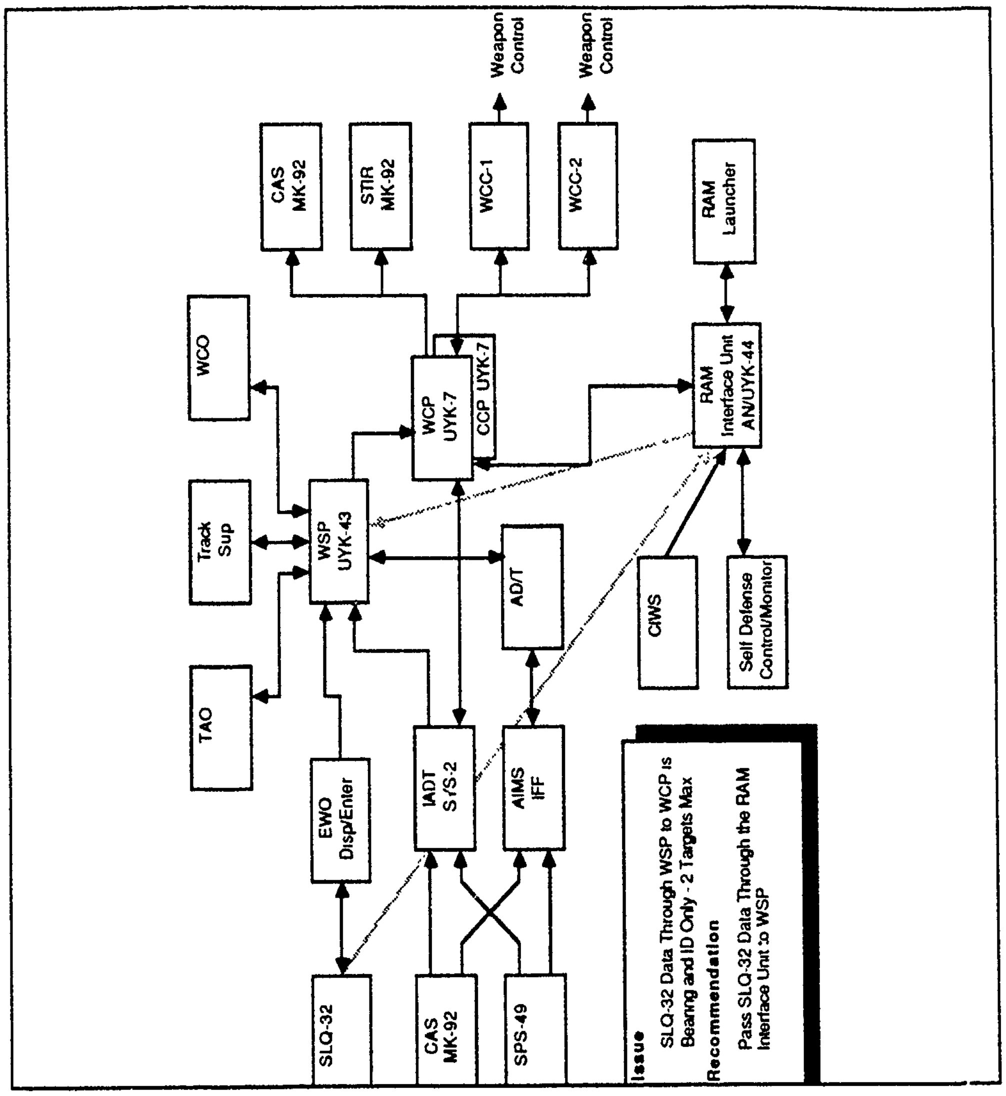

Figure 3.2.1-1. RAM/Phalanx/RIU to FFG-7 CDS Interface (NU).

(NU) The data required from the SLQ-32 for RAM engagements include frequency, power level, and bearing of the target. The frequency and power level are required to assure that the RAM missile is launched in the right RF band and will have enough power to guide in RF once airborne. The bearing is used to associate the track with radar tracks providing the range and range rate of the target. SLQ-32 data is required on all threats in the area to allow association with the radar targets for effective evaluation of all threats detected. Since no indication of the target power level is passed from the WSP to the WCP, nor is the frequency of the target passed over, it appears that the only way to meet these requirements is to have a direct connection to the RIU from the SLQ-32. Presently the only output of the SLQ-32 goes to CDS (WSP). One solution for this problem is to pass the SLQ-32 tracks through the RIU to the WSP. This concept is shown in Figure 3.3.1-1 by the dashed line from the EWO box to the RIU and back to the WSP. The RIU would then have access to all of the SLQ-32 information required by RAM and the pass through of the SLQ-32 data would be transparent to the WSP operation. This concept also has the potential of allowing the RIU to utilize the SLQ-32 if CDS goes down. This concept is recommended with more engineering work needing to be done to identify potential problems.

3.3 2 RAM/CIWS Integration (NU).

(NU) The recommended RAM/CIWS system diagram is shown in Figure 3.3.2-1. Under ground rules for this study, no functional changes were to be made to the CIWS for this system integration. The RIU can capture target data and CIWS status directly from the CIWS Instrumentation Bus available on each Phalanx mount by using a line splitter type device. Normally, these data are sent to the Parameter Analysis and Storage System (PASS) computer (a Compaq 286) to aid in CIWS failure identification and maintenance. The CIWS line splitter resides in the junction box currently placed between the Phalanx LCP and the PASS computer. This junction box currently protects the Phalanx equipment since the PASS computer is not militarized. The line splitter converts selected instrumentation bus data into NTDS A format to be sent to the RIU. The RIU receives track information from both the CIWS and from the ship CDS, if it is available. As previously stated, the RIU asssociates and correlates the different target tracks, provides track filtering to determine when a track becomes a SRAAW target, and then automatically designates the target to the RAM GMLS. If the ship CDS or ship sensors are not available, the RIU operates in a stand alone mode utilizing the CIWS radar for RAM employment. In either case, the CIWS will, in the event of target leakage, protect the ship if the threat reaches its open fire range.

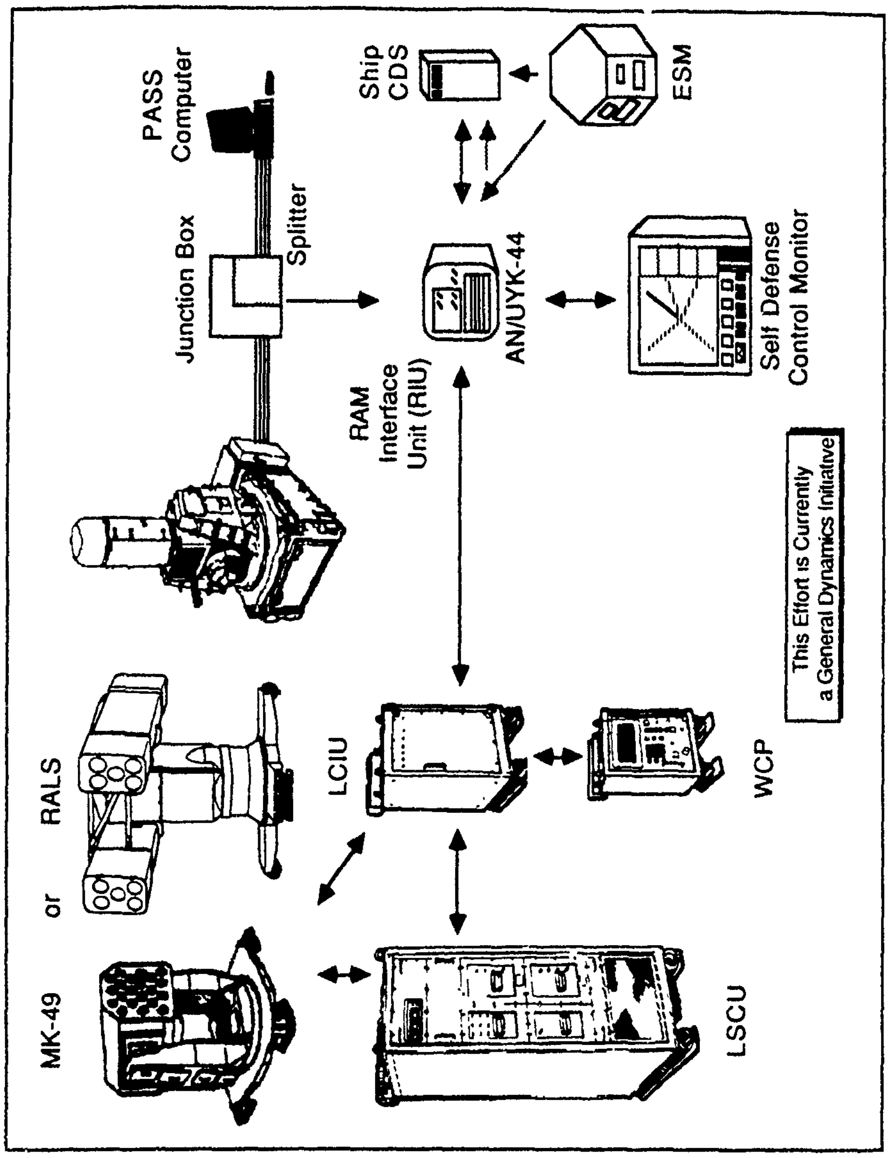

Figure 3.3.2-1. RAM/CIWS System Integration Diagram (U).

(NU) The CIWS Instrumentation Bus data are dependant upon which mode the CIWS computer is in: Search, Track, Fire, etc. The RIU could become "overburdened" with unnecessary data if the bus cannot be pre-processed or filtered. Figure 3.3.2-2 represents the Instrumentation Bus and the information the RIU needs to develop tracks from CIWS detects and shows what recommended data should flow through the filter.

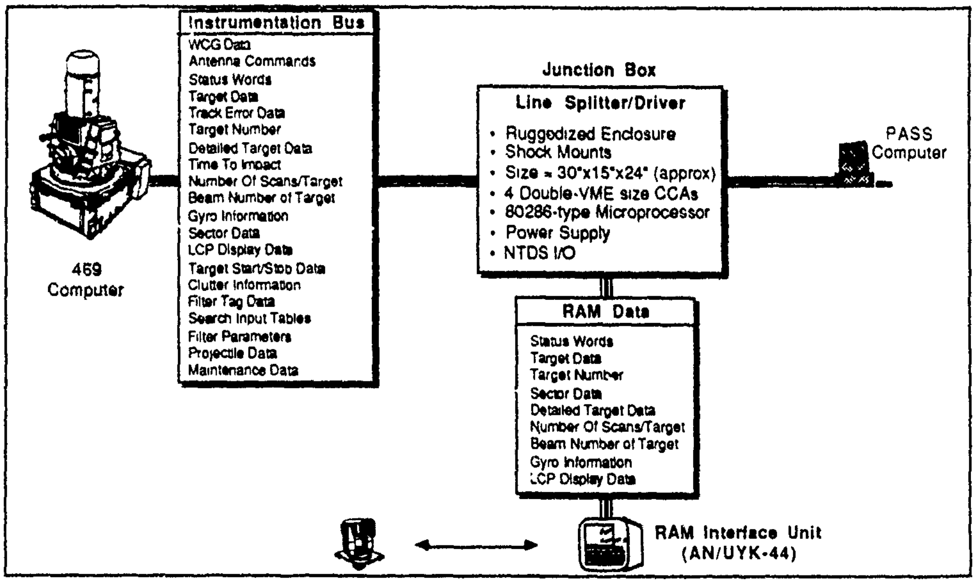

Figure 3.3.2-2. CIWS Instrumentation Bus and Recommended Filtered Data (NU).

(NU) The line splitter/filter box is enclosed within a militarized enclosure with shock mounts. The filter algorithms are performed with a computer-based system using an 80826-type microprocessor. It includes its own power supply, VME-type circuit cards, and line drivers to transmit the filtered data to the RIU. The protocol of the CIWS/RIU interface adheres to the NTDS interface standard (MIL-STD-1397A).

3.3.3 RAM Interface Unit (NU)

(NU) The RIU provides command and control processing to support execution of the RAM engagements. Though it is anticipated that RIU software will reside in an AN/UYK-44 computer, the engineering concepts presented in this section are not dependent on the AN/UYK-44 as the target computer. Figure 3.3.3-1 depicts the RIU software functional composition. The command and control mechanisms for employing RAM are currently implemented as part of the MK-23

(NU) Target Acquisition System (TAS). The TAS Operational Computer Program (OCP) incorporates pertinent functions for designating targets to the RAM GMLS. Without an interface to TAS, (e.g. the absence of a TAS aboard the FFG-7 class ship), any consideration for RAM installation must address the same functional provisions for GMLS inherent in the TAS OCP. The RIU will build upon efforts already accomplished in the TAS OCP and utilize as much of this developed software engineering as is practical to effect a solid basis for RIU development. The RIU is currently an industry initiative in the demonstration phase.

(NU) A generalized example of a UYK-44 Military Reconfigurable Computer (MRC) to support the RIU interfaces is depicted in Figure 3.3.3-2. The RIU is being designed to support inputs from up to 4 CIWS line splitters and provide designations to up to 3 RAM GMLS at any one time.

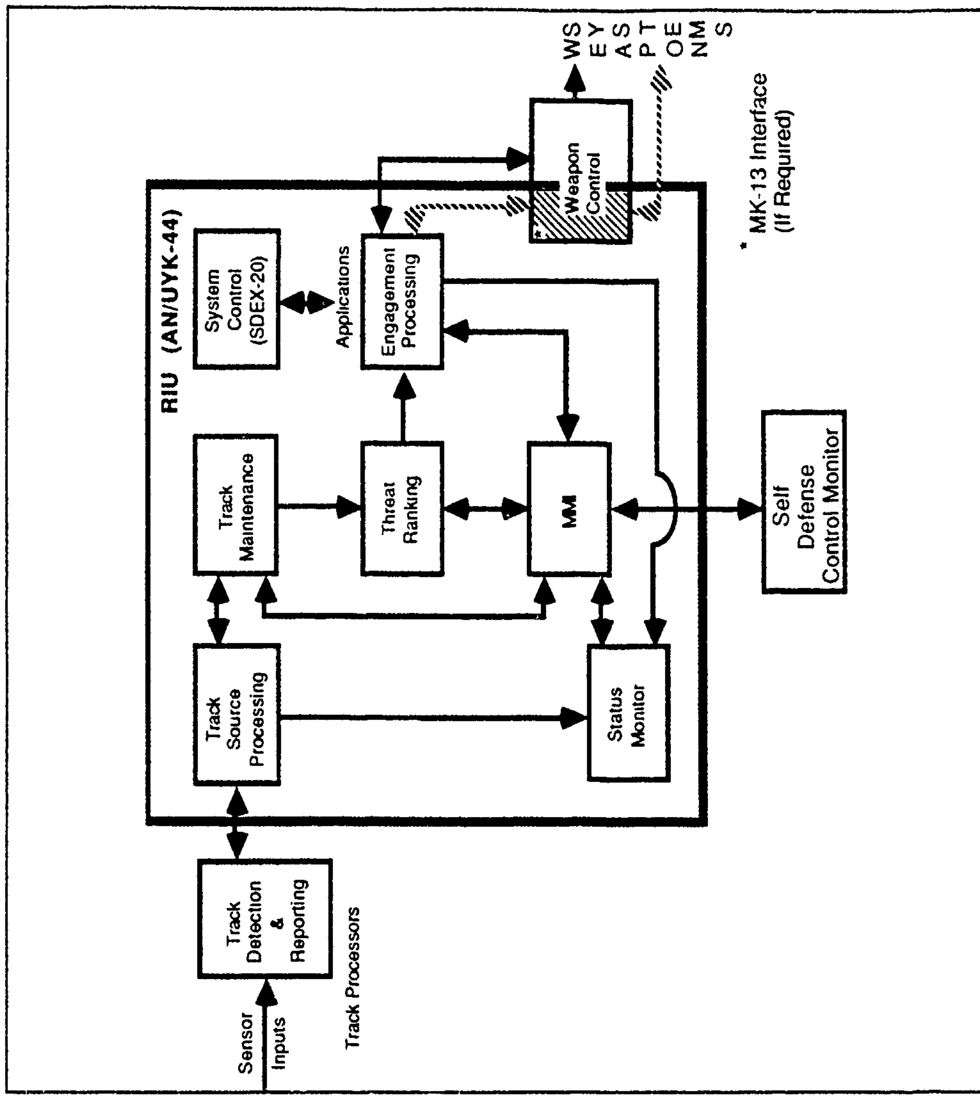

Figure 3.3.3-1. RIU Software Functional Block Diagram (NU).

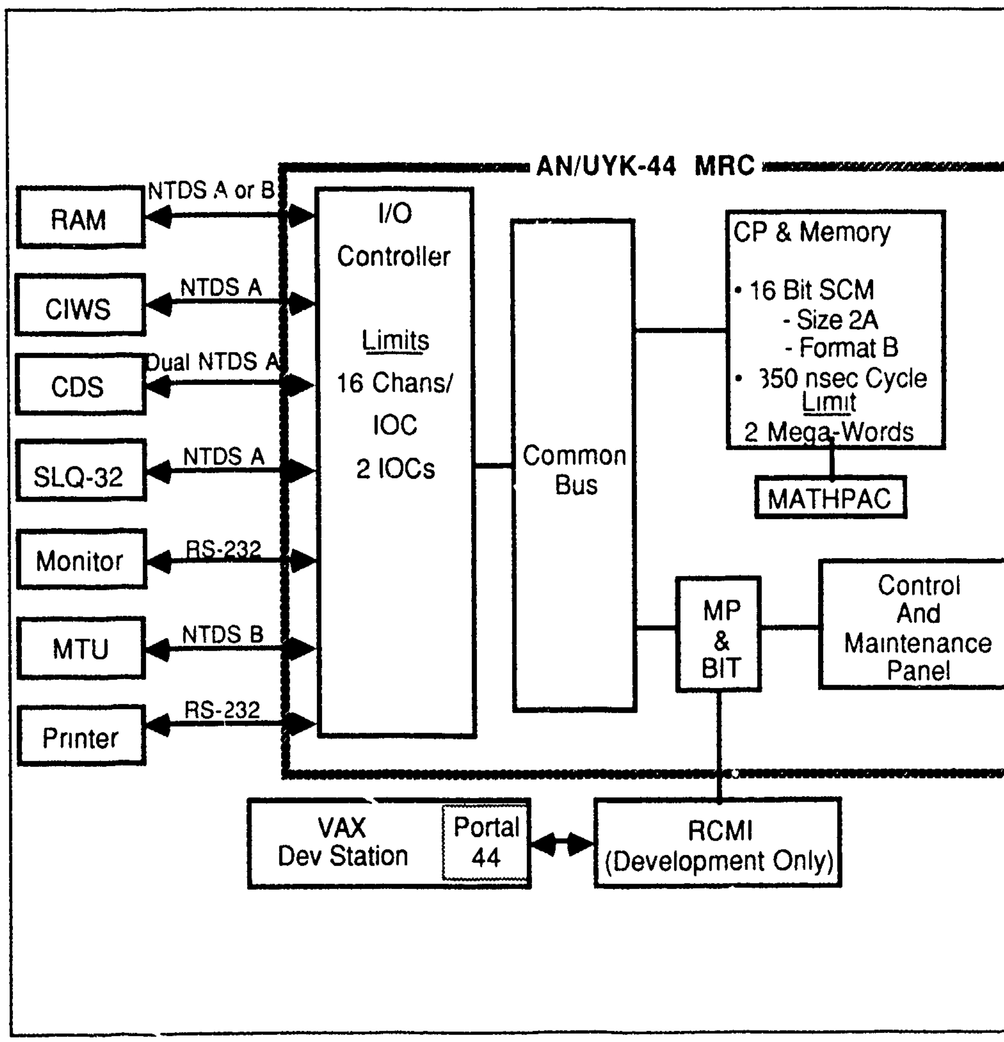

Figure 3.3.3-2. RIU Hardware/Interfaces (NU).

3.3.4 Operator Interface & Automatic/Semi-Autom..c RIU Operation (NU).

(NU) The operator is provided a tactical monitor which can provide insights into the RAM and CIWS engagement status for improved battle management. This Self Defense Control Monitor provides data input, system status monitoring, and operational engagement monitoring or over-ride capability. It is envisioned that the monitor will be a small ruggedized US Navy standard touch panel mounted near the Tactical Action Officer or the Weapons Control Operator in CIC and will require no dedicated operator (Figure 3.3.4-1).

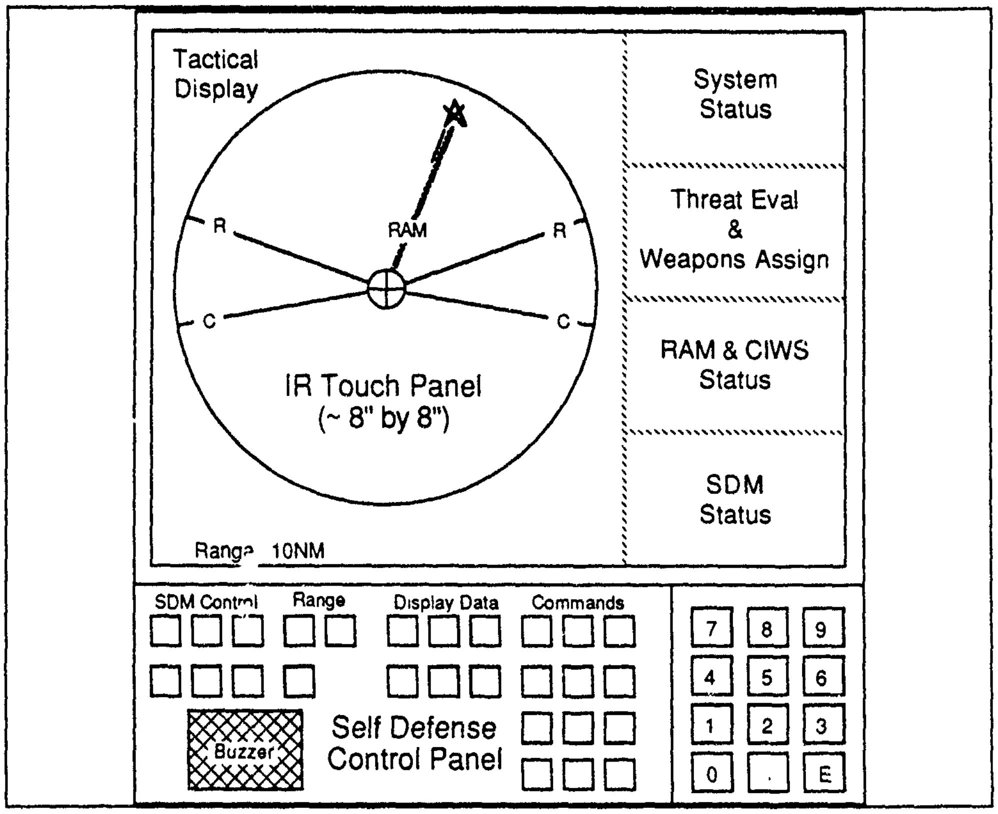

Figure 3.3.4-1. Self Defense Control Monitor (NU).

(NU) As a minimum, RAM and CIWS engagement zones and SRAAW targets received from CDS and CIWS shall be displayed. The monitor shall show pairing lines between ownship symbol and the engaged target including the engaged weapon identification. The touch panel display will allow the TAO or WCO to monitor, and if desired, to override RIU weapons assignment actions. The monitor is digitally driven by the RIU. This implementation allows stand alone display and control if CDS is down or in casualty situations. It also supports system implementation aboard non NTDS ships or ships with very limited combat systems.

(NU) In the completely automatic RIU mode, the operator has a minimum of responsibilities with this integrated system. The self defense system will detect, correlate/associate, prioritize, assign, and fire a salvo of two missiles all automatically. It will also perform survive assessment and re-engagement if necessary. The operator has the capability to override the automatic designation to the RAM system and can change the target designated using the Self Defense Control Monitor. The RIU gives a warning indicating that a RAM missile is about to be fired. The operator can see at what bearing and against what target the engagement will take place. The operator can hold fire at this time, if desired. If no hold fire is commanded, the engagement continues automatically. The operator can also select any of the targets displayed on the monitor to be engaged ("hook" by touching). This will override the automatic sequencing done by the RIU.

(NU) In the semi-automatic RIU mode, the RIU recommends that a particular threat be engaged, but will not automatically designate the target to the RAM GMLS. The operator must press the recommend designation button for the engagement to continue. This condition will also exist for the cases where there are not both radar and SLQ-32 data on a track, but the criteria is met for engagement using one of the sensors.

4.0 RAM/CIWS OPERATIONAL PERFORMANCE SUMMARY (NU).

(NU) This section provides a short summary of the integrated RAM/CIWS operational effectiveness developed as part of the study. First, an operational effectiveness baseline was established using the FFG-61 configured with the MK-92 Combined Antenna System (CAS) Mod 6 (CORT) fire control radar, the Standard Missile (SM-1), and the Block 1R3 version of the Phalanx CIWS. Next, the operational benefit of adding RAM integrated with the MK-92 was established for each of the three ship configurations described in Section 2.0. Finally, the operational benefit of also integrating RAM with the Phalanx CIWS radar coverage was established.

(NU) The anti-ship missile (ASM) was used as the threat for this analysis. The Applied Physics Laboratory (APL) of the Johns Hopkins University provided the threat characteristics. Three different ASM threats were separately evaluated: low/slow sea skimming ASMs, low/fast sea skimming ASMs, and high/fast ASMs using a diving terminal manuever. Wave scenarios using 2 ASMs at different bearings but at the same range from the ship, and stream scenarios using 4 ASMs on the same bearing with specified arrival spacing were evaluated. For the stream scenario, 75% of the ASMs were assumed to be radiating RF energy. For the wave scenario, both ASMs were assumed to be radiating. Four ASM radar cross section (RCS) values were parametrically evaluated for detection range and engagement capability. APL provided the detection range estimates for the MK-92 CAS CORT and the General Dynamics Pomona Division provided the detection range estimates and hit data for the Phalanx system. Classified details of the threat, detection, engagement, and lethality assumptions are available in the full report.

(NU) The measure of merit used for this performance evaluation was the number of ASMs leaking into the CIWS layer. This measure of merit was chosen because it allows quantification of the benefit of providing an additional layer of ASM defense. In all cases, the SM-1 system was allowed to engage the ASMs, providing the CAS CORT radar was able to establish a track and providing the engagement timeline was sufficient to allow illuminator acquisition and SM-1 flyout. The RAM system used both the CAS CORT tracks and/or the SLQ-32 ESM tracks (if the CAS CORT could not provide a track against the lower RCS targets). Additionally, the RIU used CIWS radar tracks when it was integrated with this system. This integration provided radar tracks against the lower RCS targets, but required the integrated system to be very fast due to potential close in detections.

(NU) Figure 4.0-1 presents the overall operational effectiveness results. The primary results showed that adding the high firepower, fast reaction RAM system in either the MK-49 21 round launcher or in the 2 RALS 10 round launchers reduced the ASMs leaking to the CIWS layer by 50 to 90%. The least benefit was derived against the larger RCS, slow ASMs and the most benefit was obtained against the higher speed ASMs. Additionally, the RAM's ESM only engagement capability provided significant benefit against lower RCS targets where the primary radars either did not detect or obtained a late track on an incoming ASM. The RAM system provided a significant layer of ASM defense.

(NU) When RAM was employed from the MK-13 launcher with the 2 round strongback, it provided approximately half to three quarters of the performance it achieved in the stand alone launcher cases. This performance is based upon the lower firing rate of the RAMs due to the requirement to stow or jettison the RAM strongback prior to the next RAM firing salvo. The stow and reload process requires approximately 18 seconds, and the jettison and reload process requires approximately 12 seconds. Although the operational benefit is not as great as in the stand alone launcher cases, the increase is ASM defense is still substantial if weight and moment criterion are paramount on the FFG-7 class ship.

- RAM in the MK-49 or RALS Cuts Targets Leaking to CIWS by 50 - 90 %
- RAM in the MK-13 Launcher Produces 45 - 75% of the MK-49/RALS Performance (Timelines - Stow/Jett of Strongback)
- RAM/CIWS in Casualty or Stand Alone Cases Provides 40 - 80% Cuts in CIWS Targets

Figure 4.0-1. RAM/CIWS Operational Analysis Study Results (NU).

(NU) Finally, the performance of RAM using only ESM tracks and the CIWS radar for target engagement data is shown. This situation could occur if the primary MK-92 radar was severely jammed or if the radar or primary CDS computers were casualties or down for equipment problems. In this situation, the performance is close to the full up system capability. The integrated RAM/CIWS system provides strong casualty backup for the primary radar and CDS systems aboard ship.

(NU) Figure 4.0-2 depicts relative intercept ranges for the engagement systems on the FFG-7 ship The operational analyses shows that the SM-1 system had sufficient engagement timelines versus the slow ASMs, but did not have sufficient engagement timelines against the lower RCS, high speed ASMs. The RAM system achieves a much improved intercept range against both slow and fast ASMs, helping prevent high speed debris from damaging the ship.

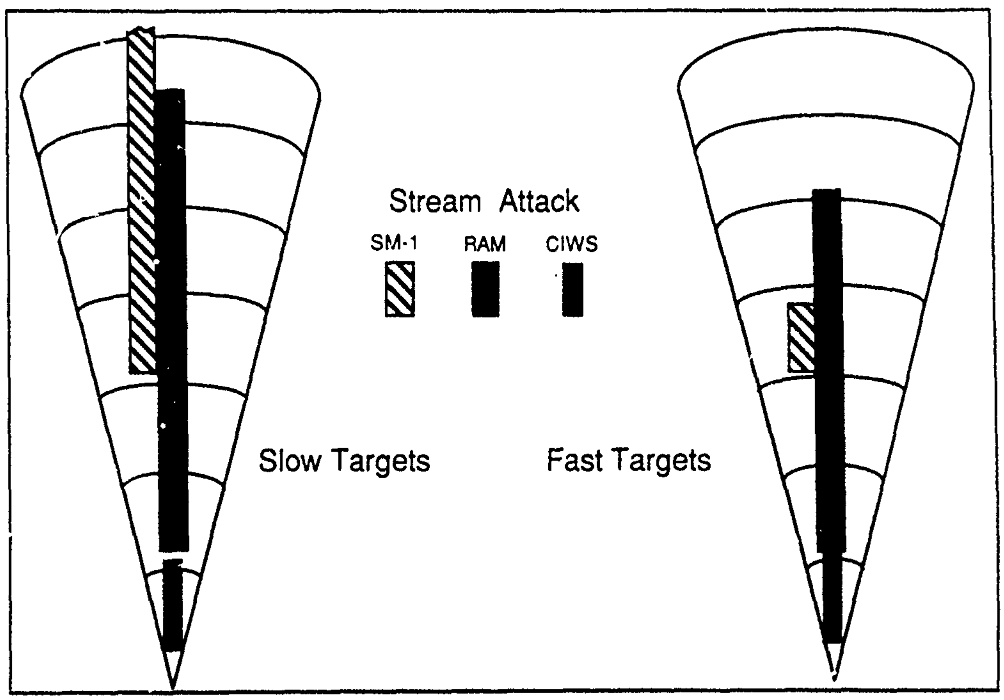

Figure 4.0-2. Relative ASM Intercept Ranges. (NU)

(NU) Figure 4.0-3 summarizes the system benefits of the RAM/CIWS integrated self defense weapon system. Adding RAM to the FFG-7 class ships, in either of its stand alone launchers, provides a strong additional ASM defensive layer. RAM's flexible engagement capability (NU) introduces less dependence on the ASM's RCS and RAM's high speed airframe provides increased ASM intercept ranges, helping reduce potential ship debris damage. Additionally, integrating RAM and the Phalanx CIWS provides strong casualty backup for existing ship combat systems. The Phalanx radar capability provides hemispherical low RCS ASM detection capability and the RAM system provides hemispherical layered engagement capability. The combination of the two systems significantly enhances ship surviveability in both low and high intensity conflicts.

Adding RAM to the FFG-7 Provides:

- Increased AAW Firepower — Cuts CIWS Targets 50 - 90%
- Extended ASM Kill Range (Less Debris) — Up to 7 times CIWS Alone
- ASM Engagement from ESM Data — Independent of RCS

In Addition, Integrating RAM/CIWS Provides:

- Radar Designation of Small RCS Targets — Using CIWS Radar
- Radar Backup of CDS, SPS-49, and CAS — ECM or Casualty
- Upper Hemisphere Layered Coverage — CIWS plus ESM

Figure 4.0-3. RAM/CIWS Integrated Weapon System Benefits (NU).

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14. Abstract: Modern anti-ship missiles (ASMs) pose a considerable threat to warship survivability. The large numbers fielded have increased the probability of a multiple axis attack, and short turn-on ranges have decreased warning time. Use of advanced electronic counter-countermeasures (ECCMs) in seekers has increased the performance required from softkill systems.

Today's softkill system design is made particularly challenging by the requirement to counter the terminal phase of a radar guided missile attack. Widespread use of monopulse angle tracking combined with other ECCMs such as leading edge range tracking and frequency agility have greatly reduced the effectiveness of traditional on-board jamming waveforms.

This paper examines an alternative to chaff, an active off-board expandable decoy for use in the protection of frigate sized vessels. The active decoy offers enhanced performance characteristics such as larger equivalent radar cross-section, less reaction time, and broader frequency coverage.

REALIZATION OF AN EXPENDABLE ACTIVE SEDUCTION TYPE NAVAL DECOY

John Nielsen
MEL-DSL

ABSTRACT

This paper will discuss the realization of a practical expendable naval decoy that is deployed by a chaff rocket. The decoy considered is of the seduction type which is designed to counter the ASM during its lock-on and terminal engagement phases. The content of this paper is a result of a feasibility study performed at MEL-DSL that was funded by DREO.

1. INTRODUCTION

It is becoming increasing difficult to counter modern ASM's fitted with active monopulse seekers using an onboard jamming system. This is because of the difficulty in impressing a sufficient azimuth angle error into the guidance system to ensure a sufficient miss distance. On-board techniques such as cros-pol or cros-eye jamming are difficult to implement and often have unpredictable effects. Contrarily, decoys can provide a definite real alternative target that is off-board and can therefore induce a sufficient angle error to provide a safe miss distance.

Passive off-board decoys in the form of chaff and corner reflectors have been effectively used ever since the second world war. However, there are several major problems with passive decoys as listed below:

1. obtaining sufficient RCS to compete with the skin echo off the ship

2. controlling the deployment position for optimum miss distance

3. deployment response time

4. obtaining a broad frequency coverage

Active decoys can potentially overcome these problem areas. It has been clearly demonstrated by simulation and actual sea trials that active off-board decoys are an effective countermeasure against radar guided ASM's. However, it has also been demonstrated that the ideal performance specifications required of the decoy results in a high cost payload. Non-expendable decoys have been considered but are not favored from an operational standpoint. Consequently, the cost of the payload must be minimized. It is desired to maintain the cost per decoy round of less than $50k.

2. OPERATION OF A SEDUCTION DECOY

Initially it is assumed that the missile is tracking the ship and that the ship and decoy are within the same radar resolution cell. For successful seduction, the decoy EIRP must be larger than the reflected skin echo of the ship. Before the missile reaches the burn-through range, the decoy and ship must separate sufficiently in azimuth angle such that ship is outside the range resolution cell centered on the decoy. Ideally, the decoy will be deployed at a sufficient lateral range to achieve this. It may be necessary to coordinate the motion of the ship to enhance the angular separation.

It is common for modern threats to use some form of leading edge track as an ECCM feature. In order to provide successful seduction it is necessary that the decoy return sweep through the ship return in range, picking up the range tracker in the process. This dictates an optimum flight path as illustrated in Fig.1. A delay is incorporated to delay the decoy return to ensure that it does sweep through the ship return.

Such a profile is possible with a controllable RPV or rocket. The RPV has been considered but due to operational difficulties, it is not a favored solution. An attractive alternative is the expendable Winnen rocket. However this is an expensive option resulting in not meeting the desired cost specification of less than $50k per round. A favored alternative is to

FIG. 1 ILLUSTRATION OF THE OPTIMUM DECOY FLIGHT TRAJECTORY

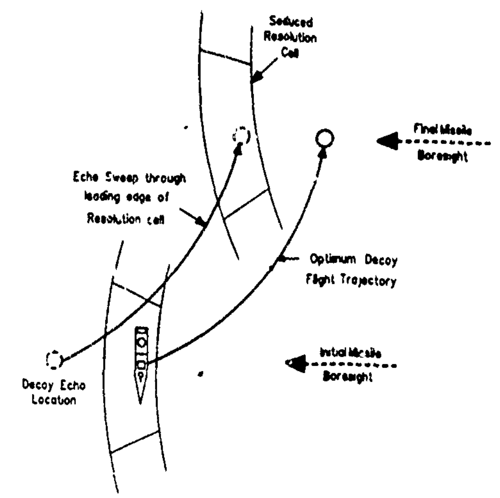
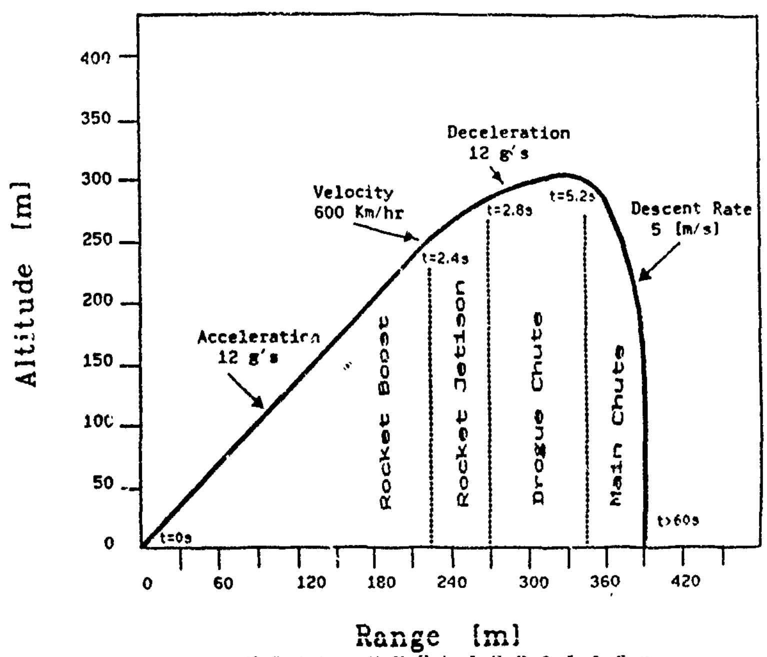


FIG. 2 CHAFF ROCKET FLIGHT PROFILE



use a chaff rocket as a deployment vehicle. It is inexpensive and uses the existing chaff launchers on board the ship. A disadvantage is that the optimum flight path of Fig.1 cannot be achieved exactly. Also, there is a possibility that the missile seeker will use range and angle velocity discrimination that can be used against the high speed chaff rocket. This limits the distance the decoy can be deployed from the ship and consequently the resultant miss distance.

Fig. 2 illustrates the various phases of the chaff rocket deployment as well as the flight profile. The rocket is launched and accelerates at about 12 G's to about 600 Km/hr. The rocket is then jettisoned and a drogue chute is used the decelerate the decoy. At a specific time, the main chute opens. This timing is used to control the deployment range of the decoy. The main chute keeps the decoy airborne for about 40 to 90 seconds depending on the height of the flight apex.

3. DECOY PAYLOAD SPECIFICATIONS

A feasibility study regarding the feasibility of the naval seduction decoy was commissioned by DREO and performed by MEL-DSL. This study concluded with a set of specifications required of the decoy round to ensure adequate success against a large number of known ASM threats. These are listed below:

1. Decoy must have a minimum EIRP to compete with the skin echo of a Frigate sized ship.

2. Frequency coverage of 7-18 GHz.

3. The payload must be launchable from by chaff rocket which severely restricts the weight and size of the payload.
    - 5 inch diameter
    - 24 inch length
    - < 25 lbs payload
    - withstand >40 G's

4. The polarization of the re-transmitted signal must be agile or at least switchable between two orthogonal polarizations.

5. The antenna coverage must be 360° in azimuth and ±45° in elevation. The azimuth coverage is necessary since the decoy is mounted on a parachute and may be oriented in any arbitrary direction. The elevation coverage is necessary to compensate for the swaying of the decoy on the parachute as well as counter high diver ASM's.

6. The decoy must be active during the launch to ensure that it is visible to the seeker.

7. The active lifetime of decoy is around 90 seconds.

8. Some pulse sorting in terms of frequency or bearing needs to be imposed in order to avoid EMI problems of jamming friendly radars.

9. The decoy round must have a 10 year shelf life under naval conditions.

10. The decoy must provide a saturated output power with the input power level ranging over 45 dB.

The objective specifications of cost, bandwidth, power, antenna coverage and small size are all conflicting resulting in an very challenging design problem. The most critical and expensive portion of the payload is the transmitter amplifier and antenna which, therefore, forms the center of the tradeoff analysis and the focus of this paper.

4. PAYLOAD OPTIONS

In the section the design tradeoffs of the decoy payload will be discussed. The performance of the payload with respect to the above specifications is determined primarily by the transmitter amplifier and antenna. Hence the discussion of payload options will be focused on these components.

Consideration will be given to TWT, solid state and magnetron based transmitter amplifiers.

4.1 Single TWT

A significant amount of effort has been expended on realizing an expendable wide-band helix TWT with about a 1 to 2 KW output. This is the bases of the payload developed for the US NULKA program. The tube cost with power supply is anywhere between $10k and $30k depending on which source is quoted. Such a tube is applicable to the chaff rocket launched decoy payload. A possible payload scheme is shown in Fig.3. A single wide-band horn antenna is used of about 10 to 15 dBi which needs to be steered mechanically in azimuth and elevation. In addition, a polarization servo is required to facilitate the polarization of the threat. A coax or BAW delay line is used to delay signal to allow TWT to turn on and provides time for any EMI filtering such as frequency or pulse width to be performed.

The main disadvantage of this form of payload is the mechanical servo required for steering the antenna in azimuth and elevation. The servo must be fast enough to counter the spin of the chaff rocket which is necessarily induced to provide stability and placement accuracy during deployment. It must also be sufficiently robust to withstand the high G forces and the 10 year shelf life under naval conditions.

An additional disadvantage is that the antenna cannot be active during the launch phase. This severely limits its effectiveness in seduction of high resolution radar seekers.

4.2 Retrodirective Phased Array Approach

The mechanically steered antenna can be avoided by either using an omni-directional antenna or by using an electronically steered phased array. The omni-directional approach is not viable since the transmitter power required becomes excessive. A coupled cavity TWT would have to be used

FIG. 3 SINGLE TWT CONFIGURATION

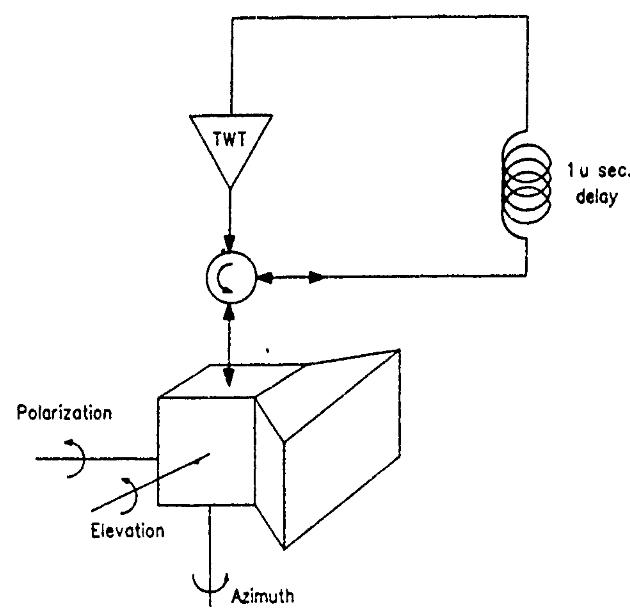
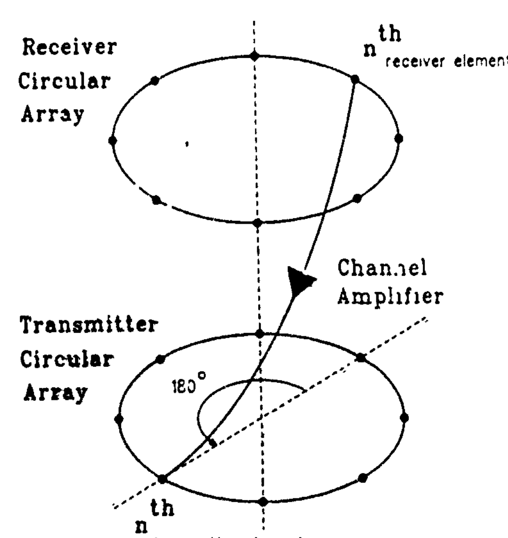


FIG. 4 CIRCULAR RETRODIRECTIVE ARRAY



which only has a narrow bandwidth. The option of using a phased array is generally considered too expensive due to the requirement of high power phase shifters. However, a very interesting option is to consider the retrodirective array antenna. A suitable form of this antenna that is conformal to the cylindrical decoy payload housing is shown in Fig.4. It consists of a receiving and transmitting circular array. Feeding each transmit element is a separate amplifier with an input from an element on the receive element. The receive element is on the opposite side with respect to the transmit element as illustrated. If all the pairs of receive and transmit elements are connected in this way, the array becomes self phasing and no additional hardware is required for beam steering.

The advantage of this scheme is first that no mechanical parts are required. The array will actively beam form to a signal arriving from any azimuth direction. The beam forming mechanism is linear and independent of frequency. Consequently, the array can respond to simultaneous threats from different bearings.

There are several disadvantages of the retrodirective array. First, the radiation pattern has fairly high sidelobes. The plot in Fig.5 is of a circular retrodirective array with 10 elements arranged in a 5 inch diameter circle at 9 GHz. As seen there are significant sidelobes above -10 dB relative to the main beam. The second disadvantage is that it is necessary to maintain phase tracking to within about $\pm$ 15° between channels. The third disadvantage is that it is difficult to implement any EMI control.

The medium power helix TWT is an attractive choice for the retrodirective payload. A practical arrangement would consist of about 10 channels with 100 W midi-tubes to achieve the required EIRP. In addition a phase matched 10 channel 100 nsec BAW delay line is required to allow for the turn-on delay of the tubes.

One of the disadvantages of the retrodirective array approach is that all the channels must track each other in phase in order to focus the beam. The midi TWT has a worst case phase tracking of $\pm$15° across the frequency band for a 30 dB gain tube which is adequate. In addition the phase must

FIG. 5 RETRODIRECTIVE ARRAY RADIATION PATTERN

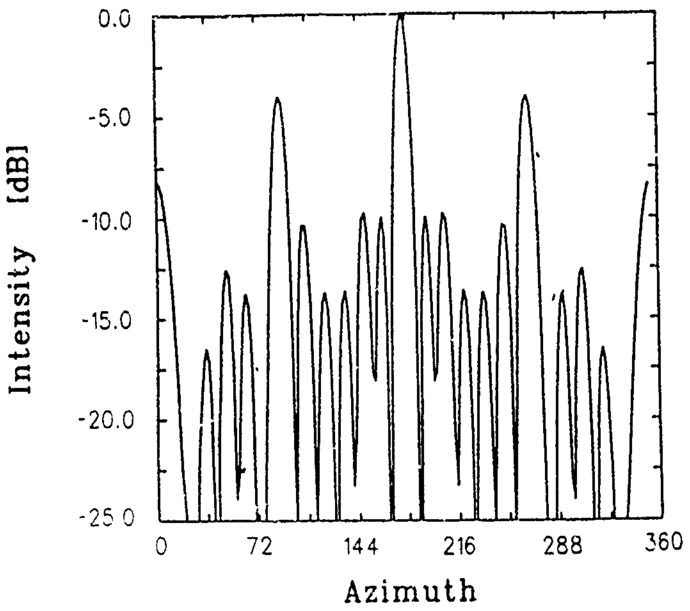
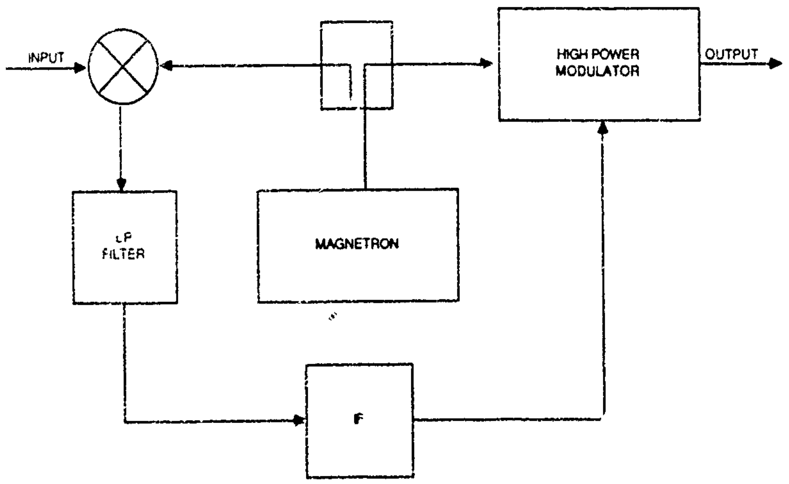


FIG. 6 MAGNETRON POWER AMPLIFIER CONCEPT



track over temperature and through the power saturation region of the tube.

In large quantities the projected cost of manufacturing a 30 dB 100 W tube is in the vicinity of S?.5k. Consequently, the cost criteria of the decoy round is achievable.

Solid state amplifiers have also been considered for the retrodirective option. Currently GaAs FET's are available that are capable of generating up to 20W of power at X band frequencies over a narrow bandwidth of less than 500 MHz. The power gain of these devices is generally less than 6 dB. The main problem with solid state is losses in the power combining sta ~s. Also designing power amplifiers is a very specialized a t which requires accurate measurement of the specific devices to be used. This makes solid state power amplifiers rather expensive. Consequently, at present, solid state do not compete favorably with respect to a midi TWT array.

MEL-DSL under contract from DREO has investigated the possibilities for using a magnetron as a pump for the bases of a power amplifier. Fig.6 shows the scheme that is considered. An IF signal is formed by down-converting the incoming signal with a sample of the magnetron output. The IF is then used to modulate the magnetron output to regenerate a replica of the incoming signal. The modulation occurs in a High Power Modulator (HPM). The HPM is a single side-band quadrature up-convertor that generates a side-band that is coherent with respect to the incoming signal.

Research into obtaining high power output at a broad modulation frequency bandwidth is ongoing.

4.3 High Antenna Gain Approach

It i difficult to achieve a solid state high power wide bandwidth transmitting amplifier at a low cost suitable for the circular array retrodirective antenna application. However, what is available are 6 to 18 GHz GaAs amplifier MMIC's which generate approximately 1 to 2 Watts. To

make use of these devices, spatial power combining is considered in a two dimensional array of significantly higher gain than the circular array considered for the retrodirective array.

An interesting observation is that in spatial power combining, if the elements are spaced apart such that the array factor directivity is less than the directivity of a uniformly illuminated aperture of the same dimension as the array then the EIRP increases as approximately N^2 rather than N, where N is the number of elements. Hence if the entire surface of the decoy cylindrical body is used, this principle can be exploited to reduce the radiated power required to meet the EIRP.

Consider the cylindrical shape of the decoy with a 5 inch diameter and a 20 inch height. The theoretical maximum antenna gain from the transmitting array panel is given by

$$\text{Gain} = 4 \pi \text{ Area} / \lambda^2$$

which at 10 GHz is 29 dBi. At this gain level, the total transmitted power required to obtain the desired EIRP is only a few watts. The actual gain will be less than this since the aperture is only partially filled. However, offsetting this is the element gain of 3 to 5 dBi. As a rough estimate it is reasonable to assume that a 24 dBi gain is possible. The main-beam would be about 6.5° in elevation and 26° in azimuth.

There are several problems in realizing a wide band high gain phased array. First, a DF system must be provided that is sufficient accuracy to steer the beam. The second problem is in phasing the elements accurately.

The accuracy of the DF required should be better than half the beam-width. Consequently a DF with 3° bearing accuracy is required in elevation. This is a challenging design problem considering the bandwidth, input dynamic range required and cost limitations imposed of the expendable payload. Hence the DF accuracy in elevation will restrict the antenna gain achievable.

CONCLUSIONS

In this paper a very brief outline of the technical challenges of realizing a seduction expendable decoy has been considered. It is difficult, with current technology to meet the performance criteria outlined in the list of specifications given and maintain a cost of less than $50k per decoy round.

Two viable solutions have been discussed, one based on A TWT array in a retrodirective array configuration and the other, a solid state phased array approach. As the GaAs technology matures, and with it the availability of wide bandwidth power amplifiers, this solution will become more cost effective.

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14. Abstract: The exhaust plumes and visible areas of the engine exhaust ducting associated with marine gas turbines are major sources of infrared (IR) radiation on ships. In recent years significant efforts have been made to reduce or eliminate these high-radiance sources to increase the survivability of naval and commercial ships when sailing in high-risk areas of the world. Typical IR signature suppression (IRSS) systems incorporate film cooling of visible metal sources, optical blockage to eliminate direct line-of-sight visibility of hot exhaust system parts, and cooling air injection and mixing for plume cooling. The present paper briefly described the motivation for incorporating IRSS into the exhaust systems of marine power plants. IRSS hardware developed in Canada by the Canadian Department of National Defence and Davis Engineering Limited is presented along with details of their operating principles.

Suppressing the Infrared Signatures of Marine Gas Turbines

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The exhaust plumes and visible areas of the engine exhaust ducting associated with marine gas turbines are major sources of infrared (IR) radiation on ships. These high-radiance sources make excellent targets for IR-guided threats. In recent years significant efforts have been made to reduce or eliminate these high-radiance sources to increase the survivability of naval and commercial ships when sailing in high-risk areas of the world. Typical IR signature suppression (IRSS) systems incorporate film cooling of visible metal sources, optical blockage to eliminate direct line-of-sight visibility of hot exhaust system parts, and cooling air injection and mixing for plume cooling. Because the metal surfaces radiate as near black bodies, every attempt is made to reduce the temperatures of the visible surfaces to near ambient conditions. The exhaust gases radiate selectively and therefore do not have to be cooled to the same degree as the metal surfaces. The present paper briefly describes the motivation for incorporating IRSS into the exhaust systems of marine power plants. IRSS hardware developed in Canada by the Canadian Department of National Defence and Davis Engineering Limited is presented along with details of their operating principles. A typical installation is presented and discussed. Design impacts on the ship are described with reference to engine back pressure, noise, and weight and center of gravity effects.

Introduction

Naval ships, and in some parts of the world commercial ships, are exposed to the risk of attack by infrared (IR) or partially IR-guided threats. IR as a means of guidance is popular because of its passive nature. That is, an IR-guided threat relies on the electromagnetic radiation emitted by the target, not on the reflection of radiation originating from the threat.

The IR signatures given off by the exhaust uptakes and the exhaust plumes of marine gas turbines make excellent targets for IR-guided threats. Over the last decade, the Canadian Department of National Defence has supported the development of devices for suppressing the IR signatures of marine gas turbines with the ultimate goal of fitting Canadian Navy ships with this hardware. The devices described in this paper are now in the construction phases for the Canadian Patrol Frigate (CPF) program and the update program for the DDH 280 destroyers (TRUMP).

IR Radiation

Thermal radiation is emitted by a body as a result of its temperature. Any body above 0 deg absolute radiates thermal energy. As described by Hudson (1969), thermal radiation lies in the range from about 0.1 to 100 μm in the electromagnetic spectrum. The IR spectrum lies approximately in the range from 0.75 to 1000 μm. Subdivisions of the IR spectrum include the near IR (NIR 0.75–3.0 μm), the middle IR (MIR 3.0–6.0 μm), the far IR (FIR 6.0–15 μm) and the extreme IR (XIR 15.0–1000 μm).

Common engineering materials tend to emit radiation throughout the IR spectrum, that is, they act approximately as gray bodies where the emissivities are constant for all wavelengths. Gases, however, tend to radiate selectively over narrow bands of the electromagnetic spectrum. The exhaust uptake metal surfaces therefore radiate as near gray bodies while the exhaust plume radiates selectively.

High-temperature bodies tend to radiate more energy at lower wavelengths (higher frequencies) and low-temperature bodies radiate at higher wavelengths (lower frequencies). A cool ship hull will radiate thermal energy at longer wavelengths than the hot uptake metal surfaces, which will tend to radiate at shorter wavelengths.

The atmosphere absorbs IR radiation except in certain regions of the electromagnetic spectrum. These regions of the spectrum through which IR radiation can pass are known as atmospheric windows. Two important windows are located at approximately the 3 to 5 μm and the 8 to 12 μm ranges. Low-temperature bodies will radiate more in the 8–12 μm range while hot bodies will tend to radiate more in the 3–5 μm range. Engineering materials, as mentioned earlier, will radiate in both these windows. Exhaust gases containing carbon dioxide and water vapor will radiate primarily in the 3–5 μm range because of their selective radiating characteristics.

The thermal radiation from the exhaust plume is due to the carbon dioxide and water vapor in the plume. As described

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by Hudson (1969), strong emission bands occur in an exhaust plume at 4.4 and 2.7 μm. The 2.7 μm band is caused by both the water vapor and the carbon dioxide, and the 4.4 μm band is due to the carbon dioxide. For detection and tracking, the 4.4 μm band is most useful. Because the carbon dioxide in the plume is at a higher temperature and higher partial pressure than the carbon dioxide in the atmosphere, it radiates outside of the absorption band of the atmospheric carbon dioxide and therefore little of the plume radiation is absorbed by the atmosphere (Hudson, 1969).

Night vision systems use the 8-12 μm range to see items at temperatures very near to the background temperatures. Looking at objects in the 8-12 μm waveband tends to show the entire body and therefore the image is an extended one. IR-guided missiles tend to use the 3-5 μm range so that they can home in on hot spots that appear as point sources.

Detection and Tracking

An IR detector is used to discern an object from its background, while an IR tracking device is used to follow the position of a selected moving object.

For detection purposes the object must appear different from the background it appears in. If an object radiates in a manner similar to the background in which it resides, it will be very difficult to detect. For detection of an extended target, the radiation reaching the detector when it has the target in its field of view must exceed the radiation that the detector receives when it views only the background (Wolfe and Zissis, 1978). In other words, the object radiance as defined below (Hudson, 1969) must be greater than the background radiance

$$N = \epsilon \sigma T^4 / \pi \qquad (1)$$

where

N = radiance (W/sr m²)
σ = Stefan-Boltzmann constant
ϵ = emissivity

The radiant power per unit area, or irradiance (W m⁻²), reaching the detector depends on the object and background radiance (W/sr m²), the object and background relative areas in the detectors field of view, the range, and of course the absorbing effects of the intervening atmosphere.

With no atmospheric absorption accounted for, and assuming the target does not fill the field of view of the detector, the irradiance resulting from an extended target in the background scene will be

$$H = (N_t - N_b)\Omega_t + N_b\Omega \qquad (2)$$

where

H = irradiance at detector (W/m²)
N_t = target radiance (W/sr m²)
N_b = background radiance (W/sr m²)
Ω = detector field of view solid angle (sr)
Ω_t = target solid angle = A_t/R^2
A_t = target projected area (m²)
R = range (m)

From the above expression we see that the irradiance seen by the detector depends on the radiance of the extended source relative to the background radiance. If the target and background have similar radiance then it will be difficult to detect the object. For detection purposes an object radiance should be considered relative to the background radiance.

If the target is a point source then it is difficult to assign a distance and area to it and therefore it is more convenient to use the concept of radiant intensity (W/sr). Radiant intensity is the product of the object radiance and the object surface area. Using the concept of radiant intensity of the target the above expression can be written as

$$H = (J_t - N_b A_t)/R^2 + N_b\Omega \qquad (3)$$

where

J_t = target radiant intensity (W/sr)

As with radiance, radiant intensity of a target should be considered relative to the background radiance effects.

For tracking purposes the same principles apply. The target radiance must be different from the background radiance. However, for trackers it is important to have a significant contrast between the background and the target. For the same irradiance, a point target is easier to track than an extended target (Wolfe and Zissis, 1978). Trackers designed for point targets usually have degraded performance when confronted by extended targets. Therefore hot spots make good targets for trackers.

Relative Importance of IR Radiation Sources on a Ship

Sources of IR radiation on a ship include the hull (and associated elements), the visible exhaust duct metal, and the exhaust plume. The relative importance of these different sources will be shown with the following approximate analysis.

Consider a hypothetical ship where the hull, plume, and visible uptake surfaces have areas of approximately 1500, 20, and 5 m², respectively. These visible areas would apply approximately for a side view of a ship when the plume is flowing straight back from the funnel. The observer's position includes a small downward elevation angle so that part of the hot exhaust uptakes is visible. The plume area of 20 m² applies for the 3-5 μm wave band (the plume effective area depends on the waveband of interest because of its selective radiating characteristics).

Let us assume that the background is at a uniform 15°C and the hull average temperature is 5°C above the background temperature. Let us also assume that the effective plume and uptake temperaures are 400°C. This case is, of course, a simplification. Real background effects, solar heating, and non-uniformities in the hull and plume temperatures have not been considered in the analysis. Table 1 shows the assumed properties of the different IR sources on the ship, including the assumed temperatures and areas.

If these different sources of radiation were to radiate as black bodies, a certain percentage of the total radiation would fall within the two atmospheric windows. Table 2 presents the approximate percentages that result.

The hull and the uptake metal surfaces act as gray bodies and for the purposes of the present analysis it has been assumed that the emissivities for both sources are 0.95. For the plume the radiation calculation is based on the assumption that the selective radiation of the carbon dioxide can be approximated

Table 1 Assumed conditions for order of magnitude analysis of different sources of IR radiation on a ship

Source	Temperature, °C	Assumed area, m²
hull	20	1500
plume	400	20
exhaust duct	400	5

Assumed background temperature = 15°C

Table 2 Approximate percentages of total black body radiation falling within the atmospheric windows for the different sources of IR

Source	Percent black body radiation	
	3-5 μm	8-12 μm
hull	1	26
plume	4*	-
exhaust duct	28	19

*Note: For the plume radiation the percentage of black body radiation is based on the 4.3-4.55 μm waveband.

Table 3 Order of magnitude estimates of radiance and radiant intensity for the different sources (0 K background)

Source	Radiance, W/sr m²		Radiant intensity, W/sr	
	3-5 μm	8-12 μm	3-5 μm	8-12 μm
hull	1.3	33	1950	49,500
plume	74	-	1480	-
exhaust duct	985	668	4925	3340

Table 4 Order of magnitude estimates of radiance and radiant intensity for the different sources accounting for background at 288 K

Source	Radiance, W/sr m²		Radiant intensity, W/sr	
	3-5 μm	8-12 μm	3-5 μm	8-12 μm
hull	0.02	2.45	30	3675
plume	73	-	1458	-
exhaust duct	984	638	4920	3188

Table 5 Percentage contribution of sources to overall ship signature (background at 288 K)

Source	Percent contribution of sources to total ship signature	
	3-5 μm	8-12 μm
hull	1	54
plume	23	0
exhaust duct	76	46

in the 3-5 μm waveband as a gray gas radiating between 4.3 and 4.55 μm with an effective emissivity of 0.5. This assumption is based on an analysis presented by Hudson (1969) for estimating the IR signature of a jet engine exhaust. Based on these assumptions the radiance and radiant intensities for the various sources have been calculated. Table 3 presents the results of these calculations.

From Table 3 it is evident that for the present hypothetical case the plume and the uptake are by far the highest radiance sources on the ship. In terms of being hot spots, the uptake has a radiance 760 times that of the hull and 13 times that of the plume in the 3-5 μm waveband. In the 8-12 μm waveband the uptake has a radiance 20 times that of the hull. Therefore to eliminate hot spots the first priority is to cool the visible parts of the exhaust duct and the next priority is to cool the plume.

In terms of the radiant intensity all of the sources are significant. In the 8-12 μm waveband the hull appears to be the dominant source. However, this is misleading because the effects of the background have not been accounted for. Table 4 presents the same estimates but with the effects of a 15°C background subtracted out.

For the present hypothetical case, the large hull area compensates for the low hull radiance and therefore the hull becomes the most significant source in terms of radiant intensity in the 8-12 μm waveband. However, in the 3-5 μm waveband all three sources are significant. In this hypothetical case in the 3-5 μm waveband the total ship signature can be reduced by 99 percent if the plume and exhaust duct are cooled. The benefit is not as great in the 8-12 μm range with a reduction of the total signature being about 46 percent if the plume and exhaust duct are cooled. These various percentages are summarized in Table 5 and, of course, apply only for the present hypothetical case.

The above example should be considered as illustrative only. Actual ship signatures of course depend on view angles, background conditions, and many other factors. However, the analysis shows that under certain conditions the plume and exhaust duct surfaces can both be significant sources of IR radiation. Because of their high temperatures the uptakes and the plume make good targets for IR-guided threats.

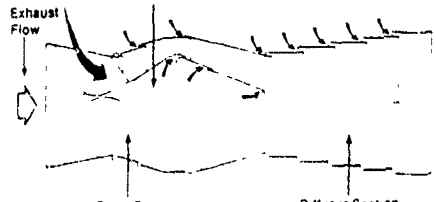

Fig 1 DRES Ball IR suppression device (marine application)

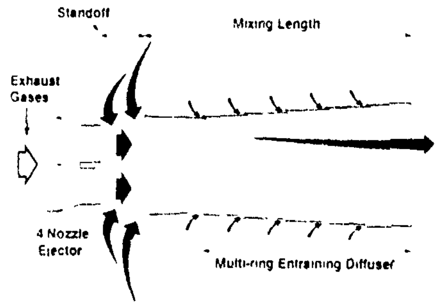

Fig 2 Eductor/diffuser IR suppression device (marine application)

IR Signature Suppression

The object of IRSS is to reduce or eliminate high radiance sources of thermal radiation. To do this it is necessary to cool the metal surfaces to near ambient temperatures and to cool exhaust plumes to a temperature where its selective radiation in the 3-5 μm band is of the same order as that from the cooled metal surfaces in the same waveband.

If the high radiance sources are eliminated then the ship becomes an extended target with no hot spots that act as point targets to a threat. With the high radiance sources eliminated the effectiveness of decoy countermeasures is significantly increased.

It should be stressed that with today's IR detection technologies it is not possible to eliminate the IR signature and thereby thwart detection. Only a fraction of a degree celsius temperature difference is needed with today's technology to detect an object. The object of IRSS is to eliminate hot spots thereby making the ship an extended target. Once this is done, hot spots can be artificially introduced using decoys.

Typically, engine exhaust IRSS systems involve film and convective cooling of metal surfaces, dilution plume cooling, and optical blockage to eliminate direct line of sight view of hot metal parts. Special finishes are also used to modify the radiating characteristics of surfaces.

Two examples of engine exhaust IRSS devices are the DRES Ball and Eductor/Diffuser (E/D). Figure 1 shows the DRES Ball device and Fig. 2 shows the E/D device.

The DRES Ball device concept originated at the Defence Research Establishment Suffield (DRES) in Alberta, Canada. The device consists of a film-cooled outer duct surrounding a convectively and film-cooled optical block center body and a film-cooled diffuser. The center body or ball is used to block the view down into the exhaust duct, thereby eliminating the direct line of sight of the hot ducting. All visible metal surfaces

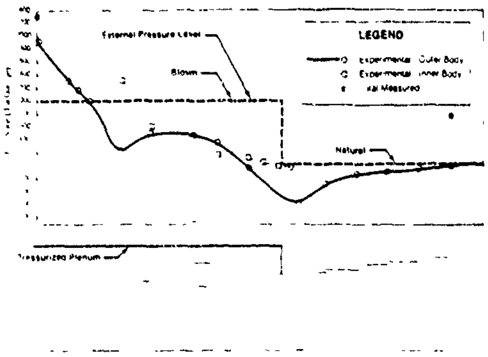

Fig 3 Flow channel pressure distribution in RES Ball device (for fan assisted design)

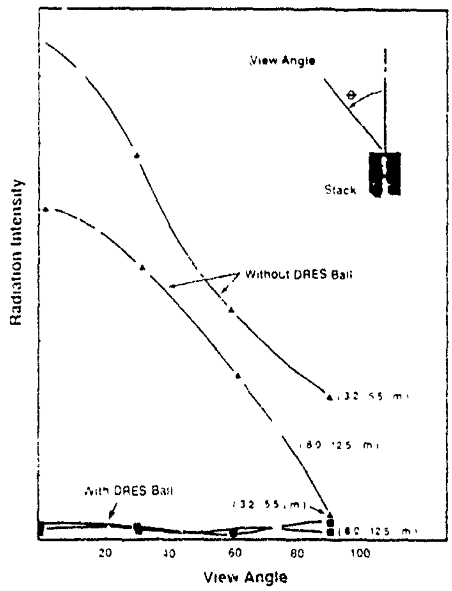

Fig 4 Measured IR signature for a scale model uncooled stack and a scale model DRES Ball equipped stack (absolute radiant intensity scale removed)

are either convectively cooled or film cooled. The film cooling layers eventually mix with the primary exhaust stream, which results in effective cooling of the plume. Cooling air introduced by the center body results in cooling of the plume core Cooling air for the center body is brought into the device through the four hollow support struts for the center body The DRES Ball provides IRSS for all angles of view.

Figure 3 shows the flow channel pressure distribution in a fan-assisted DRES Ball device (DRES Ball can be either passive (no fan) or fan assisted). As can be seen from the figure, the pressure distribution in the device is such that air is induced to flow in through the various cooling air gaps. This flow in through the gaps provides the film cooling layers on the metal surfaces and is the source of cooling air for cooling the plume The induction of the cooling air results in momentum transfer, which in turn causes an increase in the exhaust system back pressure. Friction losses in the device also result in a small increase in the system back pressure.

Figure 4 presents the results from scale model tests of a DRES Ball device and a simple uptake. The graph shows the measured radiant intensity relative to background versus the angle of view. For security reasons the radiant intensity scale has been removed. As can be seen from the figure, the DRES Ball device results in a dramatic decrease in the exhaust system signature for both atmospheric windows and for all view angles

The E/D device shown in Fig. 2 consists of an ejector pump for entraining cooling air to cool the plume and a film-cooled diffuser to provide metal surface IRSS for a limited range of view angles. This device is similar to those studied extensively by Pucci (for example, see Ellin and Pucci, 1977) and are similar to systems presently in operation in several Navies E/D devices have been designed and built to provide metal surface IR suppression for view angles up to 60 deg below the horizontal (looking down from the horizontal into the vertical exhaust duct). Because the cooling air is only introduced at the periphery of the duct, the plume temperature distribution shows a temperature peak at the plume centerline. This type of plume temperature results in a higher plume signature than that from the DRES Ball for the same average plume temperature.

Ship Design Impacts

The DRES Ball and E/D devices are typically installed in the ship's funnel and replace the end section of the exhaust uptake. Figures 5 and 6 show how a typical LM2500 installation might look with either the DRES Ball or the E/D installed.

A typical installation will involve numerous aerothermal and structural considerations From an initial design standpoint the following are the most important

1 engine exhaust flow conditions, specifically the mass flow, and temperature (for design power and ambient conditions),
2 allowable back pressure,
3 available space, and allowable weight and location of center of gravity,
4 cooling air supply,
5 allowable noise levels,
6 desired plume exit velocity, and
7 desired plume and metal surface temperatures

Flow Conditions. The engine exhaust flow conditions are obtained from the engine manufacturer, as is the allowable back pressure The engine flow conditions are the starting point from which the design begins.

The devices are typically designed for full engine power conditions. Experience to date has shown that at lower engine powers the devices continue to work effectively. As the engine power is reduced, the IR signatures decrease, as does the system back pressure.

Back Pressure. In both devices the cooling air pumping action results in back pressure being applied on the engine. The back pressure penalties depend on the desired IR suppressor performance and are typically in the range of 2000 to 4000 Pag (8 to 16 in W. G.), total pressure measured at the inlet to the IR suppressor (total pressure being the static pressure plus the exhaust gas dynamic pressure) Note that this back pressure includes the plume dynamic pressure, which is a loss in any exhaust system

The device back pressure is a function of the volume flow rate through the device. When engine power is reduced the back pressure is reduced because of the combined effect of lower volume flow of exhaust gases and reduced cooling air intake. If the source of cooling air is cut off such that less cooling air is drawn into the device, then the momentum trans-

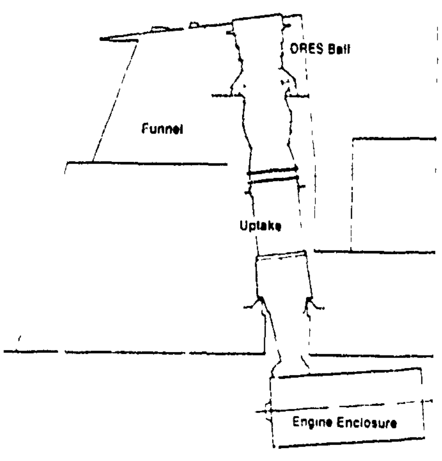

Fig. 5 Typical DRES Ball marine installation

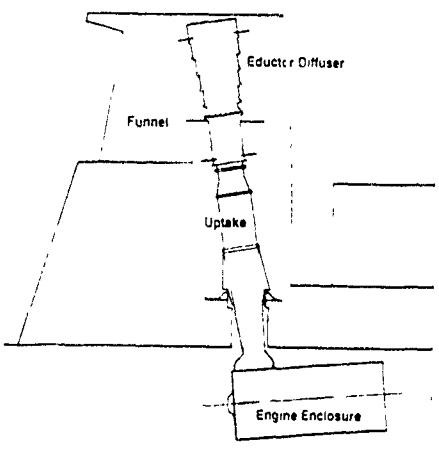

Fig. 6 Typical Eductor/Diffuser marine installation

fer effect is reduced and the system back pressure drops In other words if the IR suppressor is turned off by stopping cooling air flow then the back pressure penalty effect is reduced.

It should be noted at this time that other IR suppressor designs exist that use slightly different methods of taking in air for surface and plume cooling However, no magic method exists that gives IR suppression for free, it must be paid for in the form of fan power or back pressure for the same level of surface and plume cooling

During the initial design activities for an IR suppressor, discussion with the engine manufacturer is necessary to ensure that the exhaust system and IR suppressor design meets the

Table 6 Size, w 'ght, and CofG summaries for DRES Ball, E/D, and simple uptake for a typical LM2500 installation

	Length, m	Maximum diameter, m	Mass, kg	C of G, m
simple uptake	7 4	2.2	4200	3 7
DRES Ball	7 4	2 9	4250	3 4
E D	8.2	3.0	2800	5 5

Note The DRES Ball and E D above are passive designs and therefore do not require fans or sealed plenums.

allowable limits for engine back pressure. To date, every design involving either the DRES Ball or the E/D has met the allowable back pressure constraints set by the engine manufacturers

Space, Weight, and Center of Gravity. Another critical design consideration is the space into which the device is to fit and the acceptable weight. Because the devices are mounted high up in the ship, the weight and center of gravity of the devices is critical, especially in retrofits where much of the weight margin of the ship has been used up over the years

Table 6 presents a summary of the device dimensions and approximate weights and centers of gravity for the two devices sized for an LM2500 installation, along with the same data for a typical uptake for comparison purposes. As can be seen from the data, the devices require some additional space In terms of the device weight, the E/D is lighter than the simple uptake by a considerable amount, while the DRES Ball is of similar weight The weights of the devices have been optimized through extensive structural analysis for the reasons noted above Note that in all cases the uptake and IR suppressor material is assumed to be stainless steel sheet metal with appropriate stiffening With use of advanced material the weight effects can be reduced as much as 40 percent at a cost

Cooling Air Supply. Both the DRES Ball and the E/D device are capable of naturally inducing the required cooling air for cooling the plume and metal surfaces. That is, they are both passive devices and do not require fans

As can be seen from Figs. 5 and 6, both devices require that air freely enter the ships funnel Both devices rely on large volumes of cooling air being available at near atmospheric pressure. Pressure losses resulting from the cooling air flow through funnel louvers must be kept to a minimum Care must be taken to place the funnel louvers such that air flow can efficiently reach the devices Care must also be taken to position the louvers so that radiation of noise to critical areas is minimized.

In some cases air at above atmospheric pressure may be available, and where possible this air should be used to boost the performance of the device This air may be exhaust air from an engine room, for example. Fans can also be used to boost performance. For designs incorporating fans the fan intakes must be carefully placed to minimize losses while at the same time considering weight, space, and fan noise effects

Since the devices are completely housed in the funnel the effects of wind should be at a minimum. However, circumferential pressure variations at the cooling air gaps are inevitable, and therefore some surface temperature variations will be found in the devices. These temperature variations usually have little effect on the overall IR signature In special cases where local hot spots result, special measures can be taken, such as the introduction of transpiration cooling holes to reduce the effect of the hot spots.

Noise. Both of the devices rely on the entrainment of cooling air by using a venturi effect The resulting high velocities generate noise. Noise levels given off by these types of devices are an important design consideration because high noise levels in areas where verbal communication is necessary can not be

tolerated From a noise standpoint the DRES Ball with its relatively closed design is superior to the E/D. For the purposes of limiting noise, maximum velocities in the devices are usually limited to 95 m/s. However, it is not always possible to meet other design targets and still meet the maximum flow velocity constraint In such cases special care is taken to ensure that noise levels meet appropriate specifications. In some cases this will involve the use of acoustic treatment of ducting and other associated surfaces.

Table 7 presents a summary of estimated noise levels for a typical installation Figure 7 shows the locations of the noise levels relative to the primary noise sources.

Table 7 Approximate noise levels from DRES Ball and E/D

Location	Sound levels (dBA) at locations shown in Fig 7 A	B	C
DRES Ball	91 6	89 9	88 8
E D	99 0	93 0	91 0

Note. Estimated full-scale levels from 1 4 scale hot flow model tests with no acoustic treatment

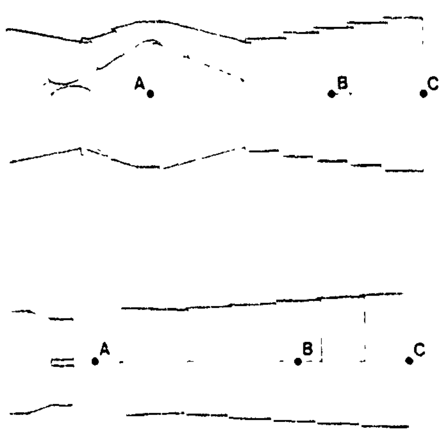

Fig 7 Location of noise measurements on DRES Ball and Eductor/Diffuser models

Plume Velocity. In some installations the plume velocity is a design constraint For the plume to clear the ship boundary layer the plume must have sufficient upward momentum: this will require a minimum plume velocity The fact that the plume is cooled must also be considered, because a cool plume is of course less buoyant.

Ship boundary layer model tests will show a required minimum plume velocity for the plume to clear the ship, and this minimum velocity has an impact on the design of an IRSS system. The higher the plume velocity, the higher the plume dynamic head, and this relates directly to the exhaust back pressure Typical plume velocities for LM2500 installations are in the order of 40-45 m/s for full power operation

The entraining diffuser on both the DRES Ball and E D is designed to reduce the plume velocity to minimize the total back pressure For installations where the desired plume velocity and allowable back pressure constraints conflict, a fan-boosted IR suppressor design may be necessary

Plume and Metal Surface Temperatures. The IR suppressors are designed to reduce the plume and metal surface temperatures The degree of cooling depends on the types of threat to be countered and on the types of decoy to be used The desired plume temperature and the engine flow conditions dictate the total amount of cooling air that must be entrained The device size, the cooling air gap areas, and the resulting flow rates fix the back pressure. The metal surface cooling dictates the placement of cooling air gaps and the shaping of the flow channel

Figure 8 shows an approximate performance map for the DRES Ball device. The map shown is for a device with uniform gap sizes and applies for a specific device geometry (fixed number and location of gaps, and flow channel shaping) The actual scales have been removed from the map for security

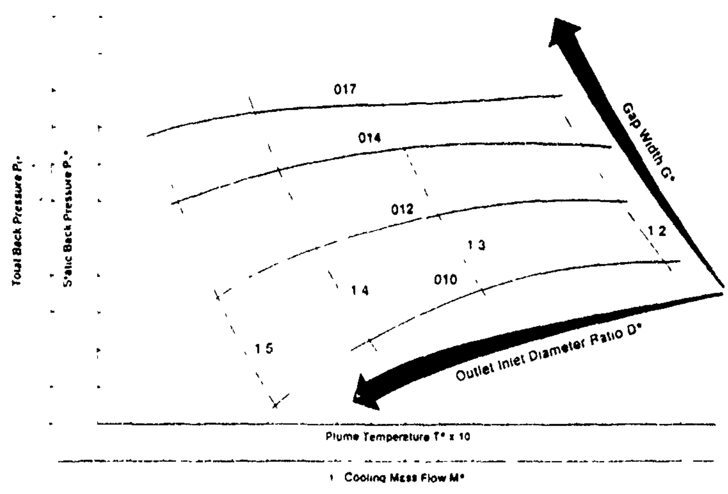

Fig. 8 Approximate performance map for DRES Ball device (temperature and mass flow scales removed)

reasons, the map is intended to show trends for discussion purposes

The figure shows a nondimensional back pressure versus nondimensional plume temperature and mass flow ratio for different device configurations The different configurations are created by varying the gap sizes and the ratio of the uptake diameter to the device exit diameter The various parameters are defined as follows:

Nondimensional plume temperature

$$T^* = (T_a - T)\ (T_e - T) \qquad (5)$$

Nondimensional back pressure

$$P^* = P_b\ 1\ 2\rho\ U^2 \qquad (6)$$

Nondimensional gap size

$$G^* = G\ D \qquad (7)$$

Nondimensional cooling air flow

$$M^* = m\ \ m \qquad (8)$$

Nondimensional size

$$D^* = D_e\ D \qquad (9)$$

where

T_e = exhaust gas temperature, °C
T = cooling air temperature, °C
T_a = plume average temperature, °C
P_b = static or total back pressure, Pag
ρ = exhaust gas density, kg m³
U = uptake flow velocity, m s
D = inlet (uptake) diameter, m
G = gap size m
D_e = exit diameter, m
m = exhaust gas mass flow kg s
m = cooling air mass flow kg s

To use the map one must select a desired engine mass flow and exhaust temperature allowable back pressure ambient temperature, uptake diameter and desired plume temperature Based on the above, the nondimensional back pressure and plume temperature can be calculated. The intersection of the vertical line passing through T^* and the horizontal line passing through T^* indicates the required gap area and device size ratio One can perform tradeoff studies by varying the gap sizes and device size and noting the effect this has on the plume temperature and back pressure.

It must be noted that this map is approximate only and does not include Reynolds number or Mach number effects. The map is presented for discussion purposes only. The above map was generated using a computer code called IRSCOOL IR suppressor design studies were conducted using this code A similar map can be generated for the E/D device.

Conclusions

IRSS of marine power plant exhausts, especially gas turbine exhausts, has been shown to have a significant effect on the overall IR signature of a ship It was shown that the engine exhaust plume and visible metal surfaces are by far the major source of radiance or hot spots on a ship. In terms of radiant intensity the ship hull was shown to be the primary source in the 8-12 μm waveband and therefore the IRSS of the engine exhaust played only a minor role in reducing the signature in this atmospheric window However, in the 3-5 μm waveband, the suppression of the plume and the hot metal of the exhaust duct had a very significant effect

Devices incorporating film and convective cooling of metal surfaces and plume dilution for plume cooling were described These devices replace the last portion of the exhaust uptake and have numerous impacts on the ship including back pressure effects on the engine, weight and center of gravity effects, and noise

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High–Precision Target Tracking in the Presence of Multipath

by

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Abstract

Multipath can adversely affect the performance of fire–control radars against low–level targets. Specifically multipath causes deep signal fades and tracking errors which can lead to reduced kill probabilities. This paper describes a new technique based on propagation modelling and maximum likelihood estimation called the Refined Maximum Likelihood (RML) technique. The RML technique is more effective than monopulse for low–angle tracking allowing a low–level target to be tracked farther into the null region. For target elevation less than .5 of an antenna beamwidth the rms tracking error can be reduced by a factor of 3 or 4 by using RML. This enhanced tracking precision may allow a reduction of the scatter on firing for the Close–In–Weapon System (CIWS).

1.0 Introduction

One of the most severe threats faced by the modern naval ship is an attack by sea–skimming missiles. Once such a missile has been launched, multipath caused by the interference between the direct radar return and that reflected from the sea surface causes large tracking errors in the fire–control radar with consequent reduction in kill probability for an engagement.

It is believed that a solution to the problem can be found by using the appropriate radar frequency bands combined with the use of array signal–processing techniques such as those described in this paper. Unfortunately, the ideal solution, comprising perhaps a dual X and K_u band radar, is probably quite expensive. Less than ideal radar systems may well be implemented in future ship–defence systems. It is interesting to note that such a wide–band system is desirable both for detection/acquisition and precision–tracking.

The precision tracking technique to be described here is based on the application of an antenna–array signal–processing technique called the Refined Maximum Likelihood (RML) technique. We therefore start with a discussion of antenna configurations suitable for the implementation of these methods. This is followed by sections on the physical basis of the RML tracking technique, the form of the RML estimators with a summary of research done on these estimators, the development of equations for monopulse and performance evaluation using simulations in which we compare the RML technique with monopulse. Finally, we discuss the implications for improved weapon–system performance.

2.0 Sampled–Aperture Antenna Configurations

A fundamental requirement for application of array signal processing is the appropriate antenna configuration. We discuss two possible configurations one of which is illustrated in Fig.1. This is the configuration used in the experimental low–angle tracking (ELAT) radar developed at DREO for the conduct of research and development on low–angle tracking techniques. The second configuration (not illustrated) corresponds to a planar phased–array MFR with subarraying on reception similar to the UK MESAR system [1]. Both these configurations can be described as sampled–aperture antennas where the aperture is subdivided into subarrays. The output of each subarray has a receiver providing in–phase (I) and quadrature–phase (Q) outputs which are digitized in Analogue–to–Digital Converters (ADCs) to give a digital sampling of the aperture. The I and Q outputs of each subarray can be treated as a complex sample; the totality of these outputs can then be treated as a complex vector for which the i^{th} component corresponds to the complex output of the i^{th} subarray.

A configuration of the second type, a planar phased array with digitized subarray outputs on reception, offers another important advantage – the ability to apply adaptive techniques for nulling jammers in the antenna main beam [2]. Indeed, this is a principal motivation for using this array architecture.

3.0 Physical Basis of the Refined Maximum Likelihood (RML) Method

In Fig. 2 we illustrate the multipath problem for a low–altitude target with a strong reflection from the sea. A common physical picture is that of Fig. 2a where we see the target and its image. Consider, however, the alternative in Fig. 2b

where the target sees a radar and its image. Here the radar and its image act as a two-element interferometer with a separation of $2h_r$ where h_r is the radar height above the sea. This picture is valid if we treat the output of our radar antenna as the output of an interferometer with a single target. The lobes of this interferometer are very sharp because h_r is many wavelengths and the peaks of this pattern can therefore be determined with precision. The ambiguous peaks can be resolved by judicious use of frequency agility over a sufficiently wide band. This is the physical basis for the RML technique which employs a model of the interferometer pattern. A propagation model using a priori information in this manner was first used in a technique called the Correlation Height Analysis (CHA) technique [3]. The interferometer model is a function of the unknown target height. The unknown target height is adjusted to obtain a least-squares fit between the model and the data vector measured across the antenna aperture. This gives the maximum likelihood estimate provided the underlying probability distribution is Gaussian.

In the Refined Maximum Likelihood method, "Refined" refers to the use of a priori information in the model for specular multipath; this information comprises knowledge of the target range (initially obtained from an acquisition radar or acquisition mode of an MFR and then maintained as part of the track update process), the complex reflection coefficient, and the specular scattering coefficient (function of sea state). By using a two-ray model for specular multipath and the aforementioned a priori information, we are able to obtain a model of the signal variation, $\mathbf{s}_m$, over a vertical aperture as

$$\mathbf{s}_m = b_m \mathbf{f}_m(h) + \boldsymbol{\eta}_m \tag{1}$$

where the index m indicates the m^{th} frequency in the case of frequency agility and where $\boldsymbol{\eta}_m$ is the vector of complex receiver noise over the array. This model has three unknowns, the amplitude and phase of the radar return, b_m, and the unknown target height, h. Knowledge of the functional form of this vector is all that is required to develop the refined maximum likelihood estimator of the target height as will be shown.

A very detailed mathematical analysis of this problem has been carried out at DREO; the details of this study are beyond the scope of this paper. We will, however, try to indicate the principal findings of this study.

4.0 The RML Estimators

The optimal target height estimators have been developed for the family of Swerling target models, 0 to IV. The Cramer-Rao bounds have been derived for Swerling 0 to II; Swerling III and IV led to intractable mathematical problems [4-6]. Extensive verification of the performance of the estimation algorithms has been carried out with Monte-Carlo simulations. Experimental verification has also been obtained using beacon signals. The baseline for performance comparison has been Fourier beamforming which is considered to produce results at least as good as monopulse. All results show that the RML performs significantly better than Fourier beamforming and by extension, better than monopulse. The better performance in comparison with monopulse will be explicitly demonstrated in this article.

The improved results cited above for the RML technique result from the use of a priori information in the propagation model. Therefore it is legitimate to ask

what happens when there are errors in the a priori information. The effects of some errors have been studied. Errors in knowledge of own radar height of about a metre can be tolerated for a radar ten metres above the sea. Some results have been obtained which indicate that the sea state must be known to within ±1 [7]. A complete sensitivity analysis has not yet been done.

In principle, each of the Swerling target models requires its own estimator. However, if the estimator for Swerling 0 is used for the other Swerling target models, a negligible loss is experienced. Here nature helps us because Swerling 0 is the simplest implementation. However, target fluctuations increase the error variance of the estimated height and increase the threshold below which useful estimates cannot be obtained. As well, the onset of the threshold effect is much more sudden with fluctuating as opposed to non–fluctuating targets [7]. In addition, for Swerling 0, I and III where the target fluctuation is slow enough to allow coherent integration, it has been shown that the optimal procedure is to coherently integrate the outputs of each antenna array element or subarray and to apply the estimation algorithms to these.

In light of the above remarks, only the equation for the RML estimator for a Swerling 0 target will be given. The form of the estimator that follows is appropriate for a frequency agile radar with m = 1 to M different frequencies. This estimator implicitly assumes that coherent integration occurs for each of the M frequency bursts prior to the estimation process. The following expression can also be used for processing completely non–coherent data; in this case the summations are extended over all the data vectors.

$$C^{n}(h) = \frac{1}{\sum_{m=1}^{M} \|\mathbf{s}_m\|^2/\sigma_m^2} \sum_{m=1}^{M} \frac{\|\mathbf{s}_m^H \mathbf{f}_m(h)\|^2}{\sigma_m^2 \, \|\mathbf{f}_m(h)\|^2} \qquad (2)$$

It has been shown [4–6], that maximizing $C^n(h)$ as a function of h gives the maximum likelihood estimate of target height. Here $\mathbf{s}_m$ is the coherently integrated data vector, the superscript "H" indicates the Hermitian transpose, $\mathbf{f}_m(h)$ is the model vector and σ_m^2 is the receiver noise power corresponding to,the m^{th} frequency of a frequency agile radar. The vector product in the numerator of (2) inside the summation sign is analogous to a Fourier transform of the array outputs; indeed when the reflection from the sea becomes vanishing small in the case of very rough seas, this inner product becomes a true Fourier transform. The superscript "n" in $C^n(h)$ indicates a non–fluctuating target. A search must be carried out over the expected values of h to determine the maximum of $C^n(h)$ which is the RML estimate of the target height. This means that the position of the target must be roughly determined using standard techniques followed by a fine search over h to determine the RML estimate.

Fig.3 shows the form of $C^n(h)$ for various sea states. This figure also illustrates what happens when the reflection weakens – the fine–structured lobing pattern starts to disappear and the precision approaches that of standard Fourier techniques.

Fig.4 illustrates, in block–diagram form, the signal–processing operations required to implement the RML technique for a radar antenna similar to that of

ELAT – suitable for a tracking radar with a single channel of fire. The extension to phased–arrays with multiple channels of fire is straight forward; the operations of Fig.4 have to be carried out for each target under track with a consequent increase in computation load.

5.0 Monopulse

Here we consider an array antenna with a vertical aperture of 2 m with Taylor weighting [8] for the sum pattern and Bayliss weighting [9] for the difference pattern. We have used $\bar{n} = 7$ and 45 dB sidelobes for both cases. In simulating both the RML and the monopulse, the array–element patterns are treated as omnidirectional. As well, the tracking performance is evaluated for targets near broadside so that beam–broadening effects are not significant.

We consider the effects of multipath and noise on the performance of monopulse in order to obtain a comparison with the RML technique. We use amplitude comparison monopulse where the angular position with respect to boresight is determined by the ratio of the difference channel output to that of the sum channel.

The equation for the voltage error ratio is given by

$$V_m = \frac{(Q_m/\sigma_m^2)\, S_m\, D_m \;+\; n_{Dm}/\sigma_m^2}{(Q_m/\sigma_m^2)\, S_m\, S_m \;+\; n_{Sm}/\sigma_m^2} \tag{3}$$

where S_m and D_m are complex propagation factors given by

$$S_m = G_{Sm}(\theta_t) + A\, G_{Sm}(\theta_{img}) \tag{4}$$

for the sum channel, and

$$D_m = G_{Dm}(\theta_t) + A\, G_{Dm}(\theta_{img}) \tag{5}$$

for the difference channel. Here $G_{Sm}(\theta_t)$ is the sum pattern response in the direction of the direct signal, $G_{Sm}(\theta_{img})$ is the response in the direction of the image and $G_{Dm}(\theta_t)$ and $G_{Dm}(\theta_{img})$ are the corresponding quantities for the difference pattern. The quantities $n_{Dm}/\sigma_m{}^2$and $n_{Sm}/\sigma_m{}^2$ represent the complex normalized Gaussian noise for the sum and difference channels,respectively. A, the complex reflection coefficient, includes the effects of surface roughness and surface curvature. The quantity $Q_m/\sigma_m{}^2$ is computed from the radar system parameters, target range and radar cross–section. We can vary this quantity to meet a desired system specification. As an example, if a system is required to produce a 10 dB free–space signal–to–noise for a 1 m² target at 25 km then we can define a term Q_0 such that:

$$SNR = \frac{Q_0 \;\; RCS}{R^4} \tag{6}$$

with $Q_0 = 3.9 \times 10^{18}$. The normalized term Q_m/σ_m^2 is then calculated from

$$Q_m/\sigma_m^2 = \sqrt{Q_0 \, \mathrm{RCS}/R^4} \tag{7}$$

with RCS = radar cross section, R = target range, m = frequency index.

The error voltage ratio is calculated using the real part of V_m and used to find the corresponding angle off–boresight. This is done for each frequency with the final estimate of the elevation angle obtained as an average over all frequencies.

6.0 Results of Monte–Carlo Simulations

We have carried out a comparative analysis of the RML and the monopulse technique by means of a Monte–Carlo simulation. The simulations were carried for the following parameters: a receiving antenna height of 20 m above the sea, an antenna aperture of 2 m, target heights varying between 10 and 100 m, two X–band frequencies, 9 and 10 GHz, and a smooth sea corresponding to sea state 2 or lower. Two hundred trials were carried out at each parameter setting and the root–mean–square error, (RSME), was computed as the average over these trials. The free–space signal–to–noise ratio, (SNR), was selected to be 10 dB at a range of 25 km for both the monopulse and the RML. The SNR increased, of course, as the range decreased.

The results presented in Figures 5–8 give the RSME in fractions of a beamwidth for four different target heights covering the low–angle region. If the target is below an elevation angle of one half of a beamwidth, the accuracy of the RML approach is three to four times greater than that achieved with monopulse. For a target entering the deepest and most distant null region, it appears that the RML technique can maintain track approximately 50 % farther than can the monopulse system as shown in Figures 9–11.

7.0 Implications for Weapon Systems

Target tracking errors impact on both the close–in–weapon system (CIWS) and the defensive missile system. In the case of the CIWS system, a spread is required to be placed on the projectiles to account for anticipated errors in the position of the target. This error is increased by multipath. If the precision of the target elevation could be increased, it might be possible to concentrate projectiles resulting in more hits on the target; this could increase the kill probability and, because of more hits, lessen the possibility of the ship being hit by debris from a disintegrating target. In the case of defensive missiles, the region of lost track when the target passes through a null can be reduced. As well, a more precise estimate of target position may impact on the required track update period and hence on the ability of the weapon system to deal with multiple target engagement.

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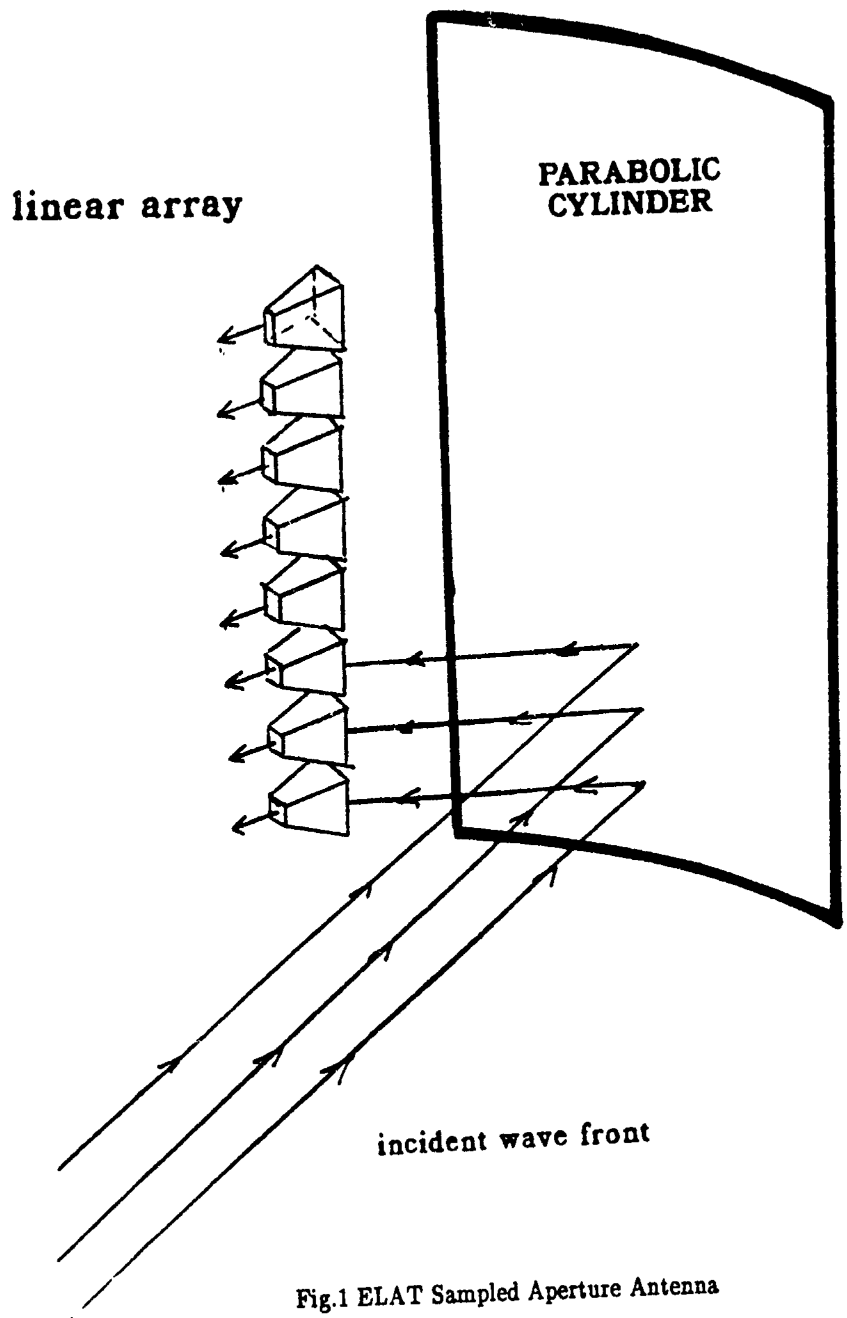

Fig.1 ELAT Sampled Aperture Antenna

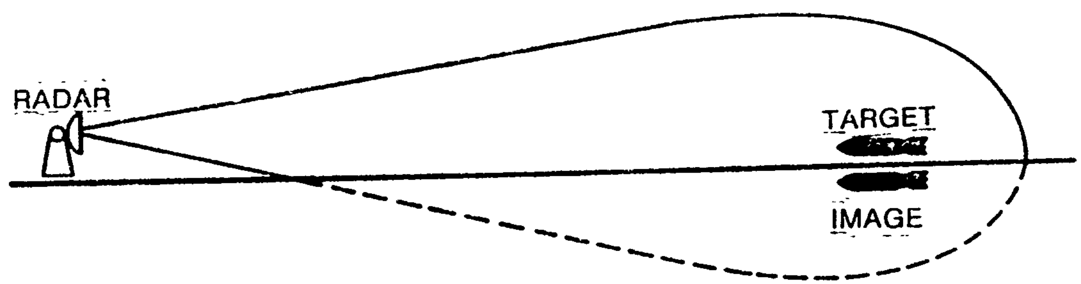

Fig.2a Target and Its Image

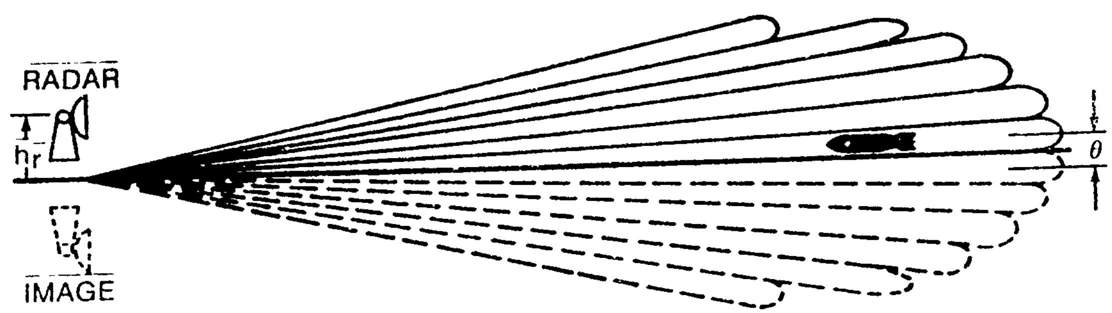

Fig.2b Radar and Its Image

24.9

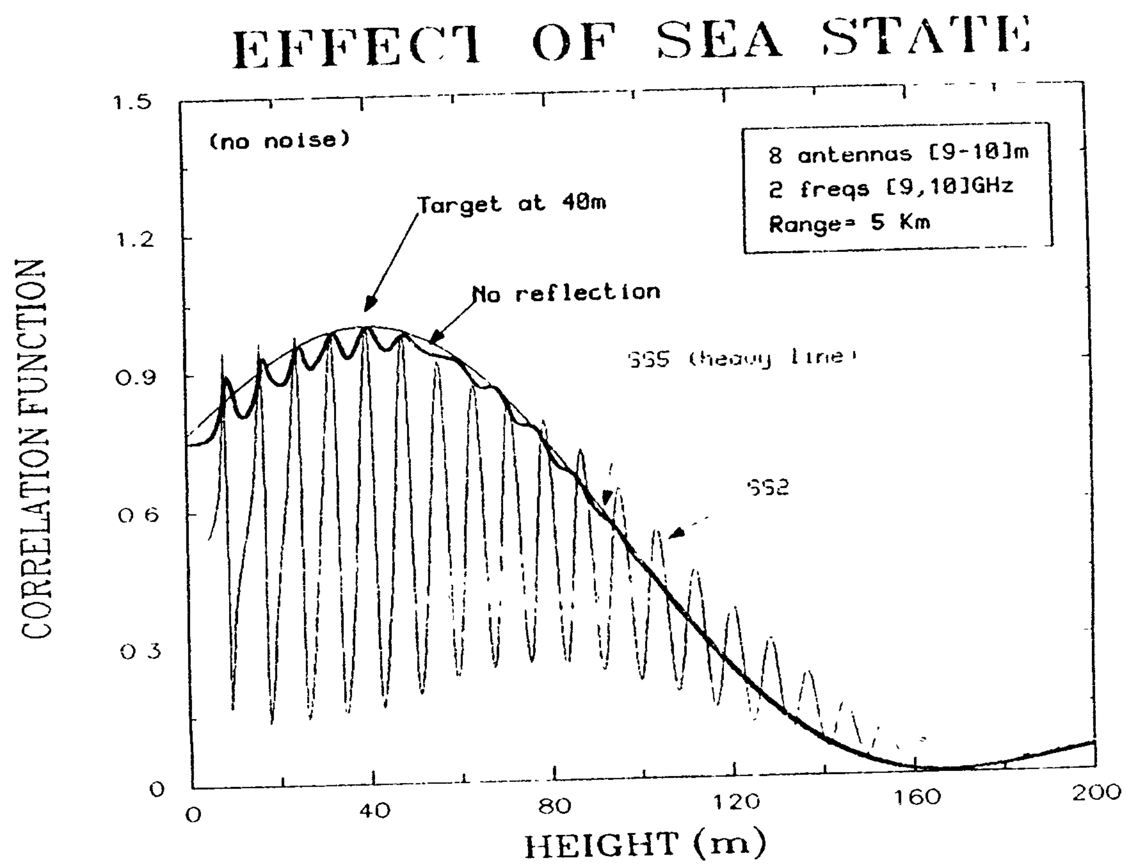

Fig.3 Refined Maximum Likelihood Estimator for Various Sea States

24.10

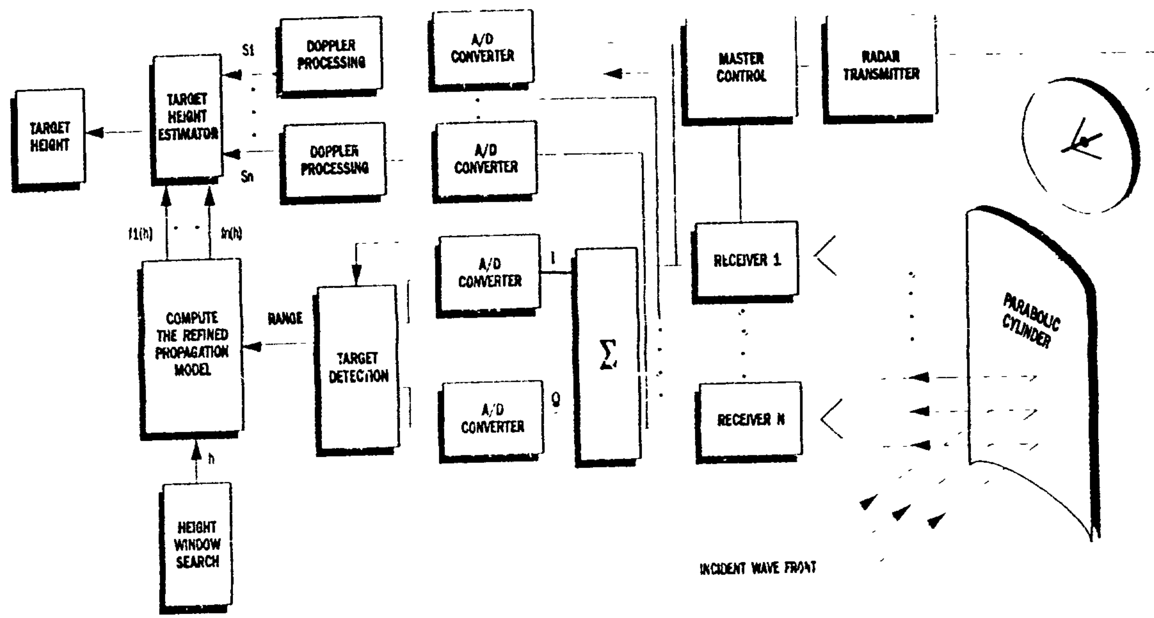

Fig 4 System Block Diagram

24.11

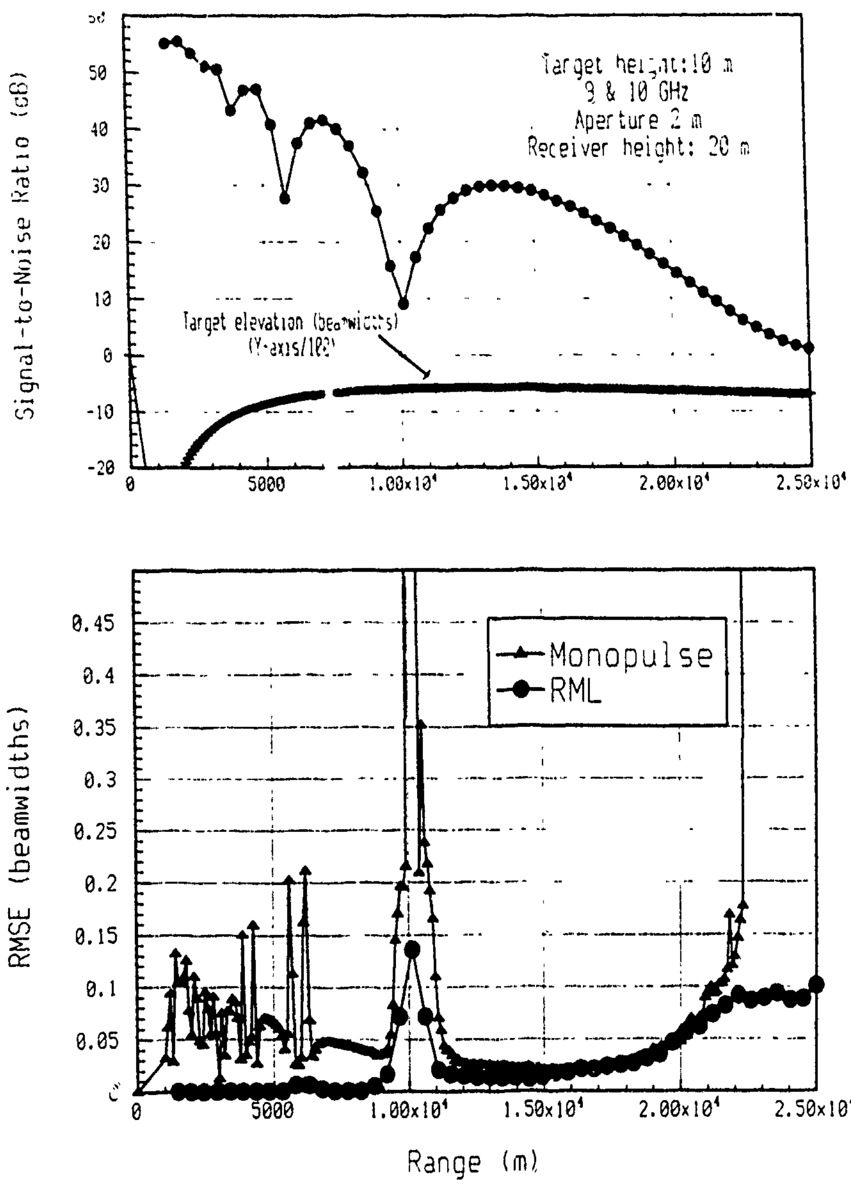

Fig.5 RML vs. Monopulse, Target Height = 10 m

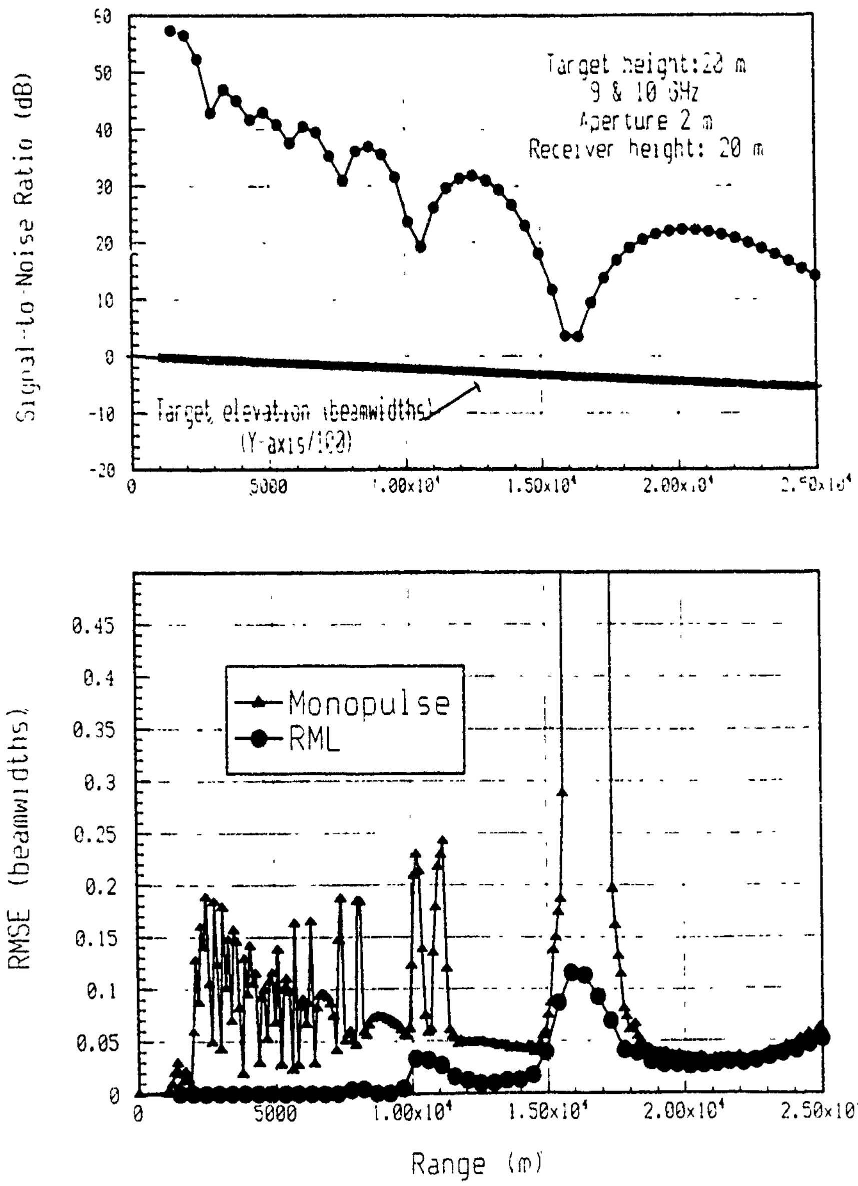

Fig.6 RML vs. Monopulse, Target Height = 20 m

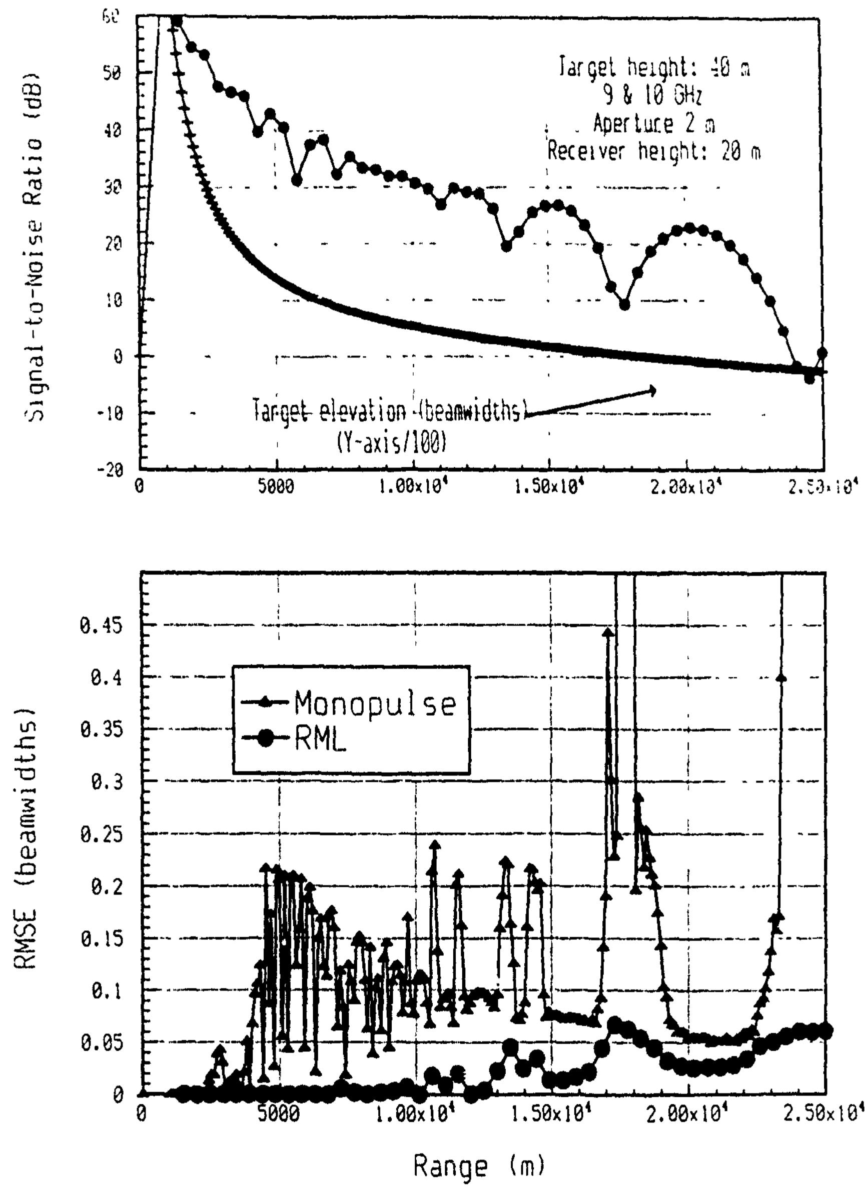

Fig.7 RML vs. Monopulse, Target Height = 40 m

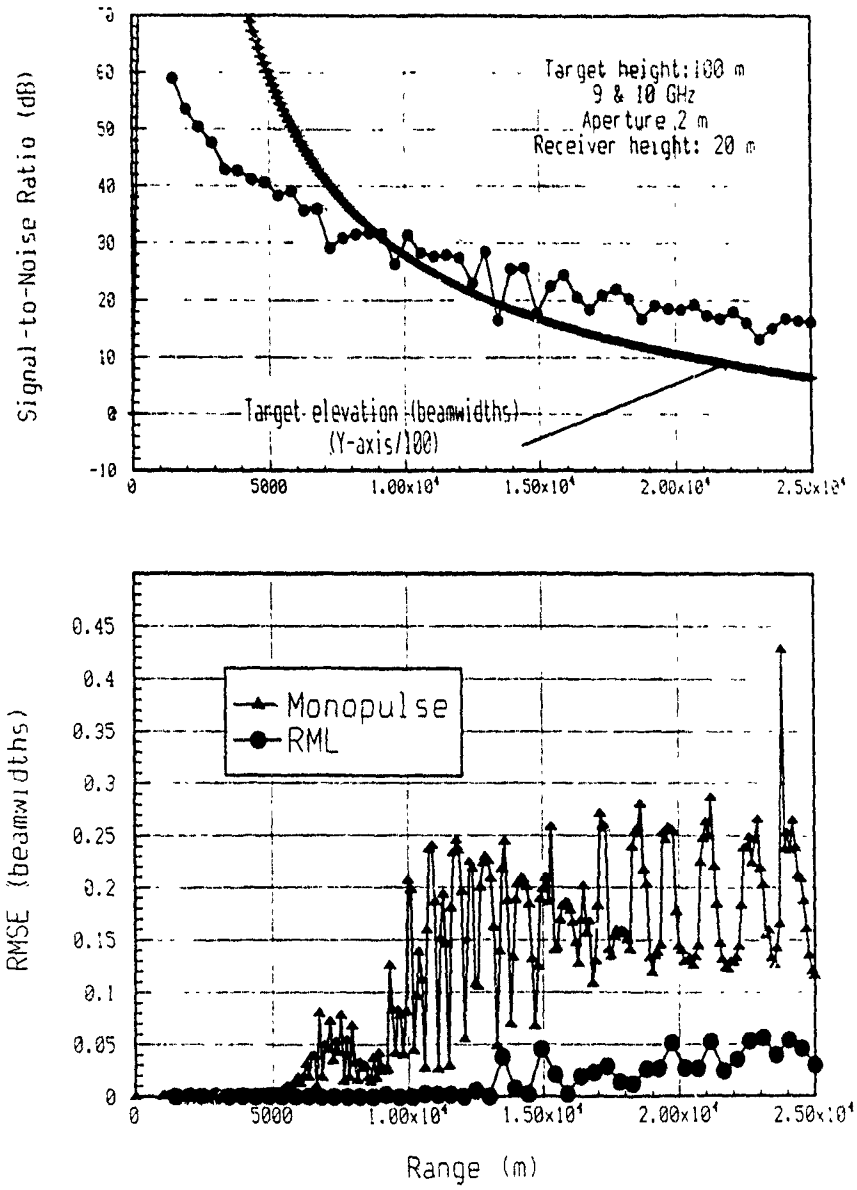

Fig.8 RML vs. Monopulse, Target Height = 100 m

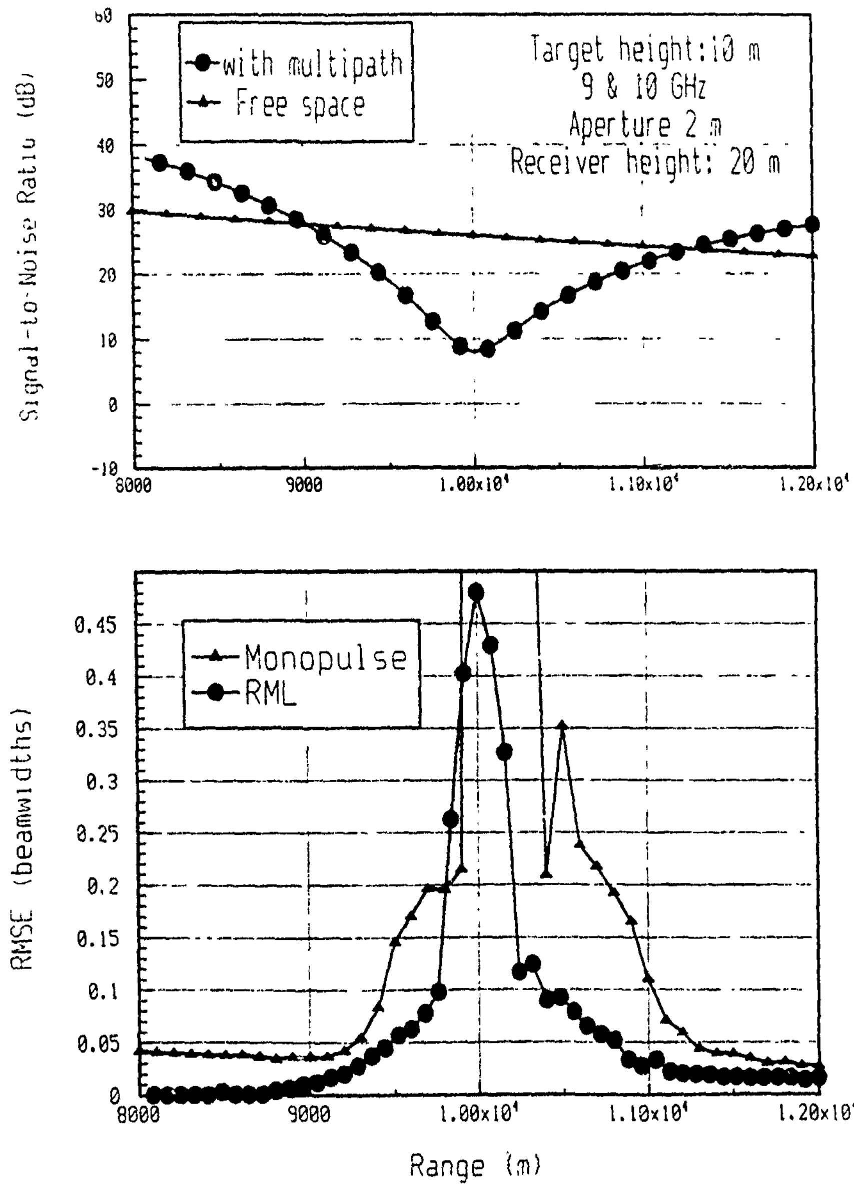

Fig.9 Performance in Null Region, Target Height = 10 m

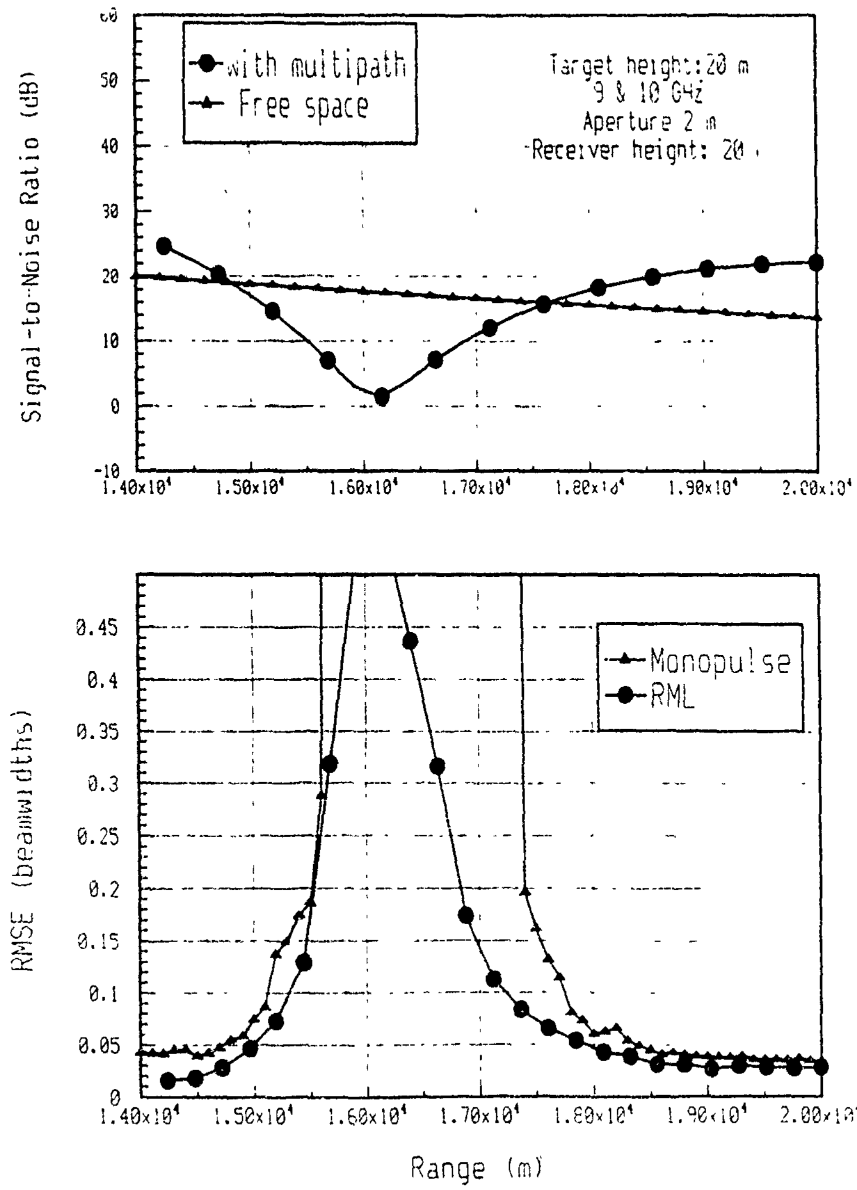

Fig.10 Performance in Null Region, Target Height = 20 m

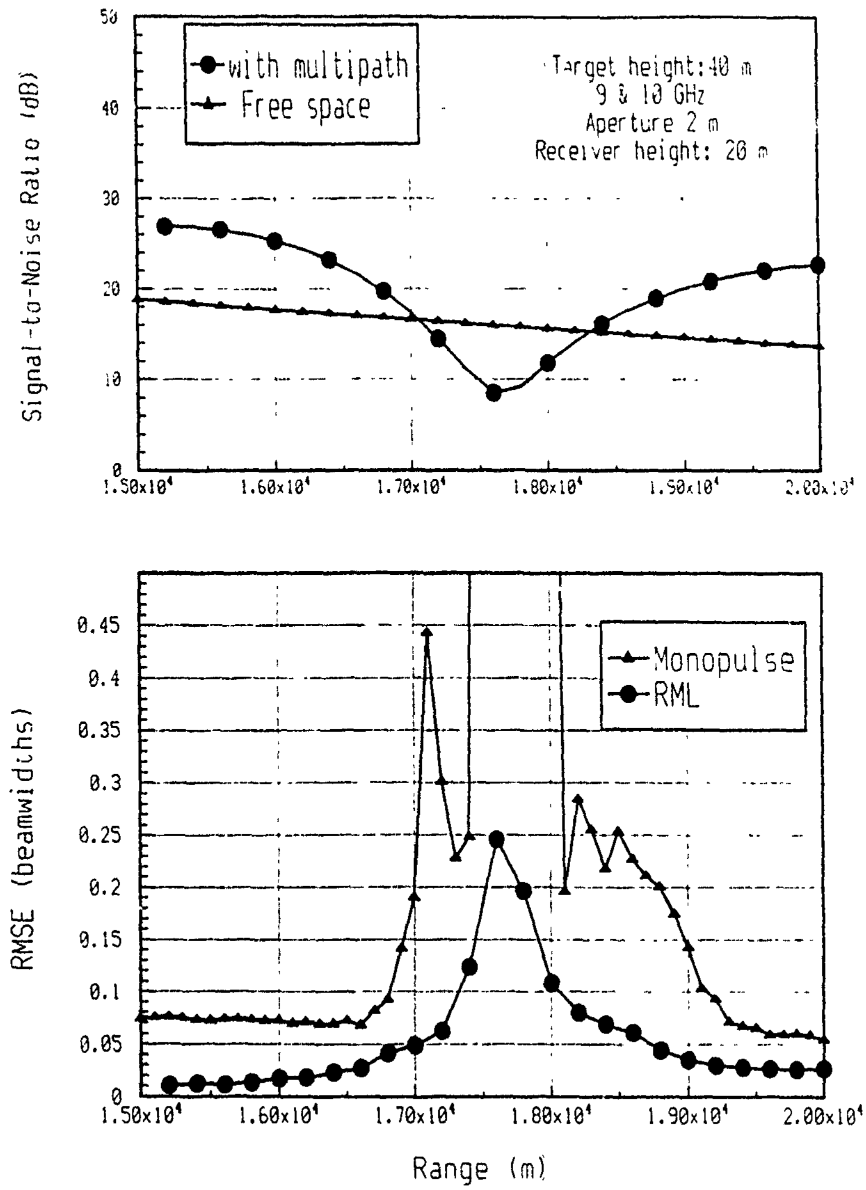

Fig.11 Performance in Null Region, Target Height = 40 m

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A COMPARATIVE STUDY OF SENSOR FUSION TECHNIQUES

by
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CONTENTS

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1. ABSTRACT

The desire to include a multifaceted sensory environment in a modern tracking system has been an underlying theme in much of the recent target tracking related literature. One of the primary concerns in such an environment is how best to accomplish the fusion of this sensory data. The term fusion as used here refers to the statistical merging of fields of sensory information which are correlated, to generate one consolidated representation.

The mathematical model used to depict the manner in which the sensor measurements relate to the quantities of interest is considered from both a quantitative (construction of stochastic models), and qualitative (characterization of failure modes) point of view so as to achieve a realistic representation of a given sensor. Other practical considerations such as differing sensory rates (collocated) combined with the desire to produce accurate predictive estimates are addressed. Both centralized and decentralized fusion structures are considered and their resulting communication requirements are compared, however, the virtues of the decentralized procedures are expounded and techniques demanding different levels of independence at the local level are discussed.

In this work a comparative survey of the currently available theoretical procedures for achieving "sensor fusion" are presented with a view to functioning in a real-time tracking environment which might possess a highly manoeuvring target shrouded in clutter

2. INTRODUCTION

The fundamental tracking problem has its roots soundly entrenched in estimation theory. As the tactical surveillance demands on the target tracking function within the overall mission strategy increases, the required theoretical base has grown to furnish these needs. The conceptual evolution of the target tracking problem can be viewed as follows:

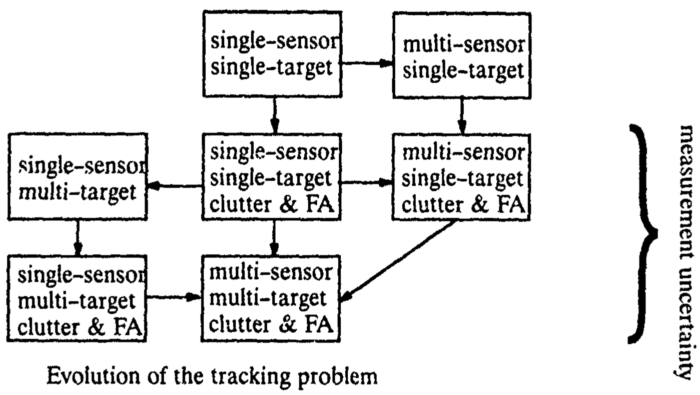

Figure 1 Evolution of the tracking problem

To accurately predict the behaviour of a target, the first phase of the single-sensor/single-target (SSST) problem requires the construction of dynamic models which adequately describe the evolution in time of the target's motion. These motion models may embody

fairly complex attributes of the target's flight dynamics, such as roll angle [1], or general orientational information [2]. Typically, the target may be observed as only a point, as is the case on a radar console, and the dynamic motion model may then take the form of a pointwise translational model. Simplifying assumptions, such as constant velocity or piecewise constant acceleration models, may also be invoked. Evasive manoeuvres performed by the target being tracked gives rise to ambiguity in the presumed known target motion model. If it is possible to isolate (and possibly characterize) the attributes of the dynamic model which give rise to this uncertainty, then it may be possible to compensate for the ill-effects of this inadequacy. The ability to track manoeuvring targets is a fundamental prerequisite for the development of a real-world tracking system.

A characterization of the manoeuvre can be achieved by an assumed statistical parameterization. Alternatively, one may have physical justification to characterize the manoeuvre as being deterministic (non-parametric) in nature [3]. An illustrative depiction [4] of available techniques might be as shown in figure 2 below.

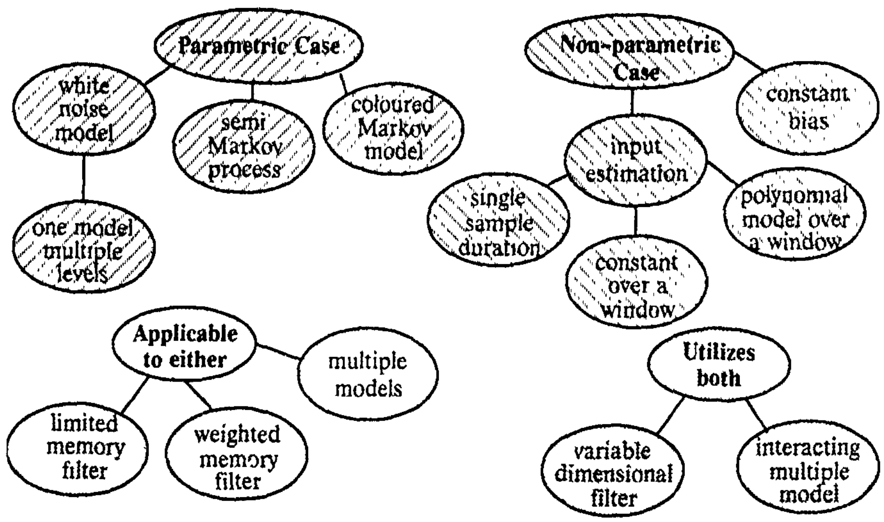

Figure 2 Classes of techniques for dealing with manoeuvring targets.

The analytical techniques employed to treat the tracking problem rely almost exclusively on Kalman filtering techniques, which in turn are dependent on the availability of linear (or linearizable) target motion and sensor models. At times, the sensory devices relied upon to collect information about the environment provide measurements which are inherently nonlinearly related to the quantities of interest being observed. Coupled with a nonlinear target motion model, one is faced with the fully nonlinear filtering problem when the linearized models yield unacceptable performance. Most results in this area have been very case specific, or of academic interest only, as is the case where determining the estimate involves infinite-dimensional computations. Recent results based on the application of Lie algebraic concepts to the nonlinear filtering problem [5] have provided motivation for

increased optimism towards the development of finite dimensional recursive nonlinear tracking filters.

Estimation techniques based on the consideration of higher order moments have recently received considerable attention, and are most commonly analysed by application of the theory of cumulants [6], which as the name implies represents a cumulative effect of the first r (say) moments by the r^{th} cumulant. These techniques are however, to-date exceptionally computationally demanding.

Having addressed the fundamental single-sensor/single-target problem in considerable detail, our research was next focused on the multi-sensor/single-target problem. The virtues of a multiple sensor tracking environment become evident when considering the improved spatial, temporal, and frequency band coverage offered by a multi-sensory surveillance system. Properly designed, significantly improved accuracy, and enhanced survivability (fault tolerance) can be realized. The requirement of fusion in meeting projected tactical needs is convincingly portrayed in a recent article [7], in which prototyping is outlined. This route was chosen as an intermediate step in the development of a viable multi-sensor/multi-target (MSMT) tracking scheme.

This paper is organized as follows: Section 3 provides a discussion of the considerations involved in the development of useful sensor models. The following section outlines an overview of proposed theoretical fusion techniques and the practical implications of each. In Section 5 the development of a proposed MSMT tracking environment is discussed. Throughout this paper, the theme of fault tolerance, and real-time applicability are stressed.

3. SENSOR MODELS

The construction of adequate sensory models that provide a coherent description of the sensors inherent capabilities and limitations, is a fundamental prerequisite for any meaningful discussion on fusing information from multiple sensors. A primary goal in developing such sensor models is to convey a quantitative description of the sensors inherent ability to extract desired information from its surroundings. Qualitative models, such as the logical sensor concept [8], which rely on an abstract definition of a sensor based on a functional description within the environment have been suggested in other disciplines. Though use of quantitative descriptions of a sensor are being stressed, they are often well complemented by qualitative assertions regarding the sensor's operation, such as a qualitative classification of a given sensor's characteristic failure modes. If the behaviour of the sensors themselves are allowed to affect how the information gathering proceeds then they play an "active" role in the collection of sensory information. A simple example of such a scenario would be a radar which dynamically changes its orientation and internal states to maintain a central perspective (line of sight) of a moving target of interest.

A formalization of the preceding notions can be achieved by decomposing the sensor model into three distinct parts, the **observation model**, the **dependency model**, and the **state**

model. An **observation model** portrays a static description of the sensor's ability to extract information from the environment, and as such is only related to the observed environment (target behaviour). This is the primary model. The **dependency model** as the name implies, describes the reliance of a given sensor's measurements on information obtained from other sensors, with which it forms conclusions. This aspect of the overall sensor model becomes important when two or more sensors function inter-dependently as a virtual sensor. A **state model** describes the association between the sensory measurements and the physical state of the sensing device, this becomes a particularly relevant model when considering dynamic sensing wherein the assumed known sensor's position (*e.g.* shipborne sensor platforms) and orientation become a factor, as they also are subject to errors, and may complicate the registration process in the multi-target case [9, pp. 155-185].

The overall depiction of the uncertainty in a given sensory measurement would require the composition of these three uncertainty models suggested above. This may be described by the interactions of the assumed apriori conditional probability density functions (pdfs).

A generalized model of the measurements (y_i) provided by the i^{th} sensor in a cluster of n inter-dependent sensors, in terms of its internal state (γ_i), dependency on pieces of information ($\underline{a}_i = a_1, ..., a_{i-1}, a_{i+1}, ..., a_n$) provided by the other n-1 sensors in the cluster, and the observed target kinematic/attribute information (x_i) of interest can be described as [10]

$$\begin{aligned} y_i &= \zeta_i(x_i, \gamma_i, a_1, ..., a_{i-1}, a_{i+1}, ..., a_n) \\ &= \zeta_i(x_i, \gamma_i, \underline{a}_i) \end{aligned}$$

where ζ_i is a possibly nonlinear but well defined function. The probability density function describing the statistics of y_i can thus be decomposed in terms of conditional density functions,

$$f(y_i) = f(x_i \mid \gamma_i, \underline{a}_i)\, f(\gamma_i \mid \underline{a}_i)\, f(\underline{a}_i)$$

where,

$f(x_i \mid \gamma_i, \overline{a}_i)$: the conditioning of the observed target kinematic/attribute information on the internal state of the i^{th} sensor and information provided by n-1 other states.

$f(\gamma_i \mid \underline{a}_i)$: describes the uncertainties of the internal state which might be dependent (not always) on information provided by other sensors.

$f(\underline{a}_i)$: the probabilistic description of the information provided by n-1 other sensors on which the i^{th} sensor is dependent.

In so doing the contribution of the three measurement models have been separated, noting however that the possibly nonlinear mapping of ζ_i may cause the density function $f(x_i \mid \gamma_i, \underline{a}_i)$ to be forbiddingly abstruse. In light of this realization, concentrating on developing adequate observation models should be stressed and contributions of state and dependency models

should be approximated to facilitate the feasibility of real time application of the above concepts.

By an indepth investigation of the underlying physical principles governing the operation of a given sensor it is usually possible to construct a tractable observation model. The development of such observation models have recently received indepth consideration: Some demonstrated examples involve airborne radars [11], ground based radar [12] and also space based radar [13]. However, linearizable additive error models are the most tractable for formulating the filtering problem,

$$y_k = h(x_k) + v_k$$

but more accurate nonlinear models can be utilized in resolving the association problem. Pdf models serve as useful guide-lines for constructing tractable sensor models, but are excessively cumbersome for practical applications. Alternative sensor models such as maximum error bounds, or Huber gross error models [10], have also been suggested

In allowing the dynamic behaviour of sensors, one must also be willing to embrace the resulting complexity incurred to achieve this flexibility Consider a mobile sensor viewing an airborne target characterized by its position and orientation,

$$\underline{x} = (x, y, z, \phi_1, \phi_2, \phi_3)$$

If the sensor relocates by a translation $\underline{a}$ and a change in orientation $\underline{\theta}$, the resulting effect on the observation model (non-linear in θ) must be accounted for, and the uncertainty $(\Delta\underline{a}, \Delta\underline{\theta})$ in this motion incorporated via the state model. This consideration is analogous to the problems encountered when sensors with multiple view points (spatially dispersed) of many targets attempt to determine corresponding targets (registration/association problem), which necessitates the use of an external coordinate system.

4. SENSOR FUSION TECHNIQUES

Assuming the existence of previously constructed models which adequately describe the sensory measurements, and appropriate dynamic models of the target(s) of interest, a framework for constructing a solution to the multi-sensor fusion problem can be developed

The "ethics" or code of optimality to which one adheres in constructing a solution to the sensor fusion problem has the singularly most dramatic effect on the resulting complexity of the solution, previous attempts to justify the linear minimum variance unbiased estimator (LMVUE) can be further substantiated in the multi-sensor case without resorting to the over used Gaussian assumption. By appealing to the central limit theorem [14] and considering the resulting probability density function (pdf) arrived at by forming linear combinations of not necessarily Gaussian[1] measurements across p sensors, the resulting pdf will be unimodal and predominantly characterized by its first two moments, although not necessarily Gaussian. Therefore, concentrating on optimizing estimates based on first and second moment descriptions appears to be both consistent and appealing.

1. There are some restrictions however on admissible classes of pdfs, for example the sum of Cauchy random variables is itself a Cauchy random variable.

Nonlinear data fusion techniques have also been described in the literature. In a recent example [15] knowledge of sufficient statistics at each local sensory node is conveyed to a global node which then constructs the global density function from the local information. In many nonlinear stochastic problems however, the existence of a finite set of sufficient statistics is questionable, and the resulting minimum variance estimate is typically not recursive and involves an infinite dimensional computation [16]. Extension of the successful Lie algebraic concepts for deterministic nonlinear (linear analytic) systems shows some promise of yielding finite dimensional solutions to the nonlinear minimum variance problem when the construction of finite dimensional estimation Lie algebras are possible [5].

4.1 Data Fusion Methodologies

Vastly differing methodologies have been successfully applied to the generic "sensor fusion" problem. Henderson [8] incorporated a qualitative description of sensor models and utilized a multi-sensor kernel system to fuse these logical sensors based on functionality. The application of heuristic rules via an expert system was demonstrated in conjunction with deterministic sensor models to obtain limited sensor fusion, while Chaudhuri [17] suggested the application of artificial intelligence techniques in conjunction with a Baysian fusion methodology. Techniques incorporating fuzzy logic [18] and neural networks [19] have also been suggested.

The majority of generally applicable techniques however, appeal to probability theory to achieve descriptions of the sensor's abilities (qualitative models) with appropriate statistically based fusion schemes. These probabilistic approaches can be further separated into techniques utilizing statistical decision theory [20], maximum likelihood techniques [21], while the majority incorporate linear Baysian estimation techniques. The viability of the linear Baysian approach for achieving practically realizable sensor fusion has been demonstrated for a wide variety of applications: The fusion of information derived from infrared (IR) and millimetre wave (MMW) sensors [22], radar and optical sensors [23], forward looking infrared and vision sensors [24], sonar and infrared sensors [25].

4.2 Determining an Appropriate information Representation level

In redundant multi-sensory systems establishing the information representation (processing) level at which information should be fused [26] becomes a sensitive concern Sensor **data level** fusion, that is fusing data at the sensor level is in general only feasible between identical sensory devices, all having the same perspective. An example of such problems becomes apparent when trying to fuse representations derived from two imaging sensors at the pixel level, although pixel level sensor fusion has been demonstrated for specific applications [24]. **Feature level** sensor fusion, when these features are discernible, provides a reasonable level of abstraction so as to facilitate the representation of only the relevant information present at the data level, thereby reducing the complexity of the fusion process for information rich sensors. Descriptions at the feature level facilitate the inclusion of orientation information which can at times be used to improve the tracking function [2]. The application of silhouettes for image based tracking of manoeuvring targets has been

successfully demonstrated [27]. Fusion at the **symbolic level** is desirable for distant targets when features of the targets are not discernible (point targets). At this level however, a simple correspondence with information present at the sensor level is sometimes difficult, and an apriori interpretation of the environment is necessary so that appropriate symbolic classifications are available. Sometimes these requirements can be adequately satisfied. For example, in ground based airborne target tracking applications where the desired goal is to track many distant targets using multiple sensors [9] classification at the symbolic level may be achieved by utilizing generic symbols with associated kinematic and attribute data. This process can be further enhanced when target signature determination is available. At this point an association between established tracks as seen by two or more sensors must then be used to fuse these tracks into one consolidated track for each symbol.

An often employed naive solution to this problem is achieved by choosing the least uncertain set of measurements and disregarding the remaining information. The pitfalls of such naive techniques is inferior accuracy, and reduced spatial and temporal coverage.

For multi-sensor target tracking systems the symbolic level seems well suited to sensor fusion problems as the kinematic and attribute information remain intact, and its associated uncertainty can be accommodated quite adequately.

4.3 Centralized Fusion

To simplify the problem somewhat assume that the model of each of the p sufficient sensory groups have been transformed to represent uncertain linearized measurements of the same kinematic quantities [4]. In general, the observation vector represents partial measurements (under-determined case) of the state vector $x(k)$, and hence will be of lower dimensionality, but due to the non-static formulation of the problem, this imposes the requirement that the overall system be observable. Furthermore, assuming the p sensors to be synchronized in time having the same sample interval (collocated sensors), models of the p sensor groups at the k^{th} sample interval can be denoted by

$$y_1(k) = C_1x(k) + v_1(k)$$

$$\vdots$$

$$y_p(k) = C_px(k) + v_p(k)$$

where the subscript refers to the sensor group number. Grouping the above yields

$$[y_1^T(k), \dots, y_p^T(k)]^T = [C_1^T, \dots, C_p^T]^T x(k) + [v_1^T(k), \dots, v_p^T(k)]^T$$

$$\mathbf{y}(k) = \mathbf{C}x(k) + \mathbf{v}(k) \tag{1}$$

Assuming all the sensors are viewing the same target, the dynamic model for $x(k)$ as seen by all sensors will be the same:

$$x(k+1) = Ax(k) + Bu(k) + w(k) \tag{2}$$

The centralized approach would use $Y = \{\mathbf{y}(0), \dots, \mathbf{y}(k)\}$ to construct a global estimate for $x(k+1)$, the decentralized approach however, would process the local information $Y_i = \{y_i(0), \dots, y_i(k)\}$ to simplify the amount of work that must be performed at a higher level

to construct an identical (analytically) global estimate. By using a standard Kalman filter with equations (1) and (2) it is possible to form a global linear minimum variance estimate of $\mathbf{x}(k+1)$ as

$$\hat{\mathbf{x}}(k+1|k) = A[\hat{\mathbf{x}}(k|k-1) + \mathbf{K}_k[\mathbf{y}(k) - C\hat{\mathbf{x}}(k|k-1)]] \tag{3}$$

and assuming the v_i's (local sensor uncertainties) to be independent

$$E[v(k)v^T(k)] = R(k) = \mathit{Block\ Diag}\,[R_1(k), \ldots, R_p(k)]$$

yields a decomposition of (3) in terms of local quantities [28]

$$\hat{\mathbf{x}}(k+1|k) = A\left\{\hat{\mathbf{x}}(k|k-1) + \sum_{i=1}^{p} \mathcal{K}_i(k)[y_i(k) - C_i\hat{\mathbf{x}}(k|k-1)]\right\} \tag{4}$$

This description obviously results in a centralized fusion technique:

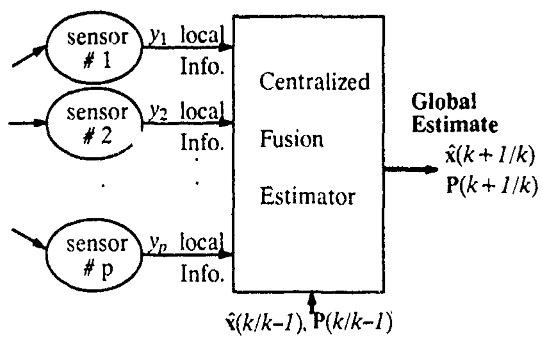

Figure 3 Centralized estimation fusion (CEF).

An alternative technique which can be utilized to achieve a centralized fusion topology requires the fusion of all the local measurements into a single measurement (with corresponding covariance) prior to estimation

$$\mathbf{y}(k) = \left[\sum_{i=1}^{p} R_i^{-1}(k)\right]^{-1} \left[\sum_{i=1}^{p} R_i^{-1}(k)y_i(k)\right]$$

This technique is commonly known as measurement fusion.

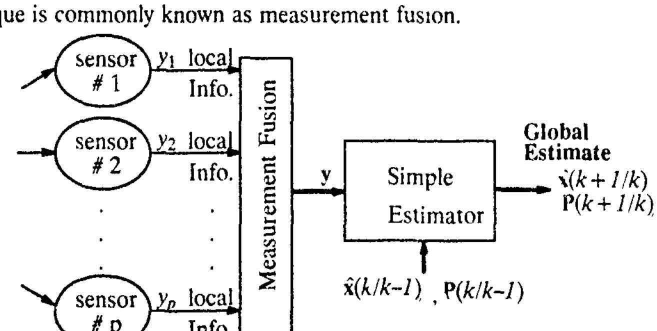

Figure 4 Centralized measurement fusion (CMF).

4.4 Sequential Fusion

A sequential filter which assumes the measurements across the p sensors are sequenced in time with zero time separation between each measurement [28] allows the local estimate to be constructed as

$$\hat{x}_i(k|k) = \hat{x}_{i-1}(k|k) + K_i(k)[y_i(k) - C_i\hat{x}_{i-1}(k|k)] \qquad i = 1,...,p$$

where

$$\hat{\mathbf{x}}(k|k) = \hat{x}_p(k|k)$$

The i^{th} sensor updates itself across one "real" sample interval using it's own information as

$$\hat{x}_i(k|k) = A\hat{x}_i(k-1|k-1) + K_i(k)[y_i(k) - C_iA\hat{x}_i(k-1|k-1)]$$

This procedure can be illustrated diagrammatically as shown below

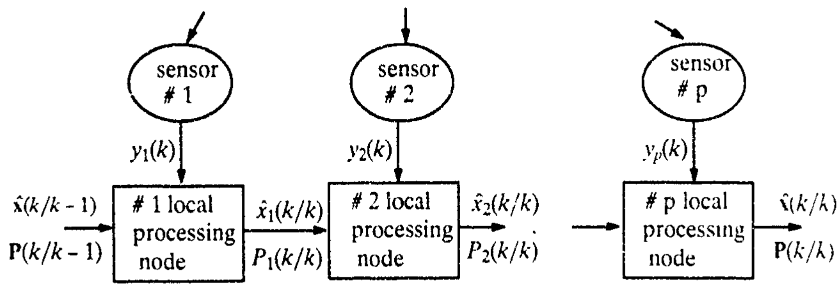

Figure 5 Sequential fusion (SF).

4.5 Decentralized Fusion

The sequential information fusion technique although being distributed is inherently time sequential in nature. An incremental improvement in the work developed by Willner was achieved by Gardner [29] via "gain transfer" wherein local gains were computed at the local sensor level but the sequential restrictions present in his predecessor's work were retained. These restrictive impositions were first lifted by Chong [30] wherein he described the construction of a global estimate from local estimates which are derived independently at each local node.

$$\hat{\mathbf{x}}(k|k) = \mathbf{P}(k|k)\Big\{\mathbf{P}^{-1}(k|k-1)\hat{\mathbf{x}}(k|k-1) + \sum_{i=1}^{p}[P_i^{-1}(k|k)\hat{x}_i(k|k) - P_i^{-1}(k|k-1)\hat{x}_i(k|k-1)]\Big\} \qquad (5)$$

where,

$$\hat{x}_i(k+1|k) = A\hat{x}_i(k|k-1) + K_i(k)[y_i(k) - C_i\hat{x}_i(k|k-1)] \qquad (6)$$

The parallel decentralized structure described above in eqns. (5) and (6) is depicted in figure 6 below.

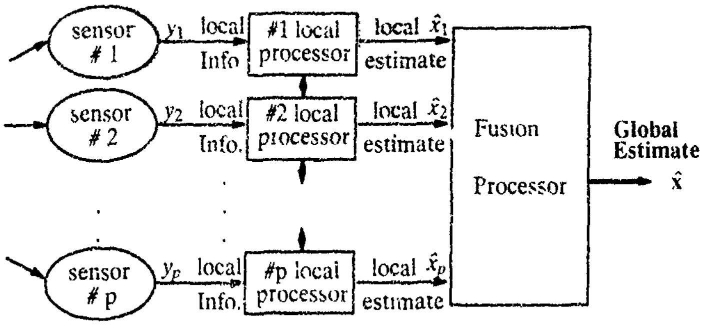

Figure 6 Generic decentralized fusion (GDF).

The work of Chong [30] represents the first truly "decentralized" sensor fusion procedure and provides an inherently hierarchical structure, which allows each local sensor group to function without requiring interaction with other sensor groups, and only to convey information to the fusion centre unidirectionally. This procedure was derived in an alternative manner (algebraic manipulation of the global estimator) by Hashemipour [31] who further generalized the approach to allow correlation between state and observation noises, and a more general state model which facilitates state coordinate transformations.

The fully decentralized approach can be achieved by reformulating the sensor fusion problem using the projection theorem [4], and advantageously exploiting information type Kalman filters at both the local and global levels. This development [4] also includes the ability to cope with manoeuvring targets by compensating ($\tilde{d}_i(k)$) local pseudo estimates as illustrated in figure 7 below

$$\hat{\mathbf{d}}(k+1/k) = A^{T}\hat{\mathbf{d}}(k/k-1) + \sum_{i=1}^{p}\left\{\hat{d}_i(k+1/k) + \tilde{d}_i(k) - A^{-1}\tilde{d}_i(k/k-1)\right\}$$

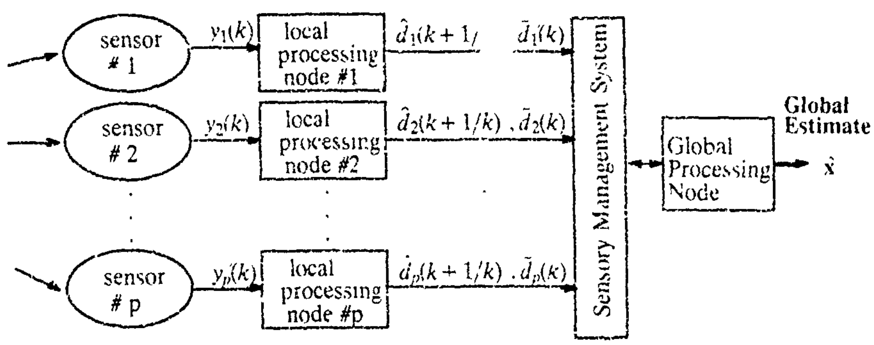

Figure 7 Decentralized information type fusion (DIF) with sensor management

Noting that the predictive estimate of the global state vector is obtained by solving the following simple linear equation

$$\hat{\mathbf{d}}(k+1/k) = \mathbf{P}^{-1}(k+1/k)\hat{\mathbf{x}}(k+1/k)$$

In the event that a sensory group should fail, the use of failure detection techniques should be utilized. A consensus approach to deriving confidence regions within the three dimensional target motion space has been extensively studied in the context of detecting abrupt changes in signals and dynamic systems [32].

4.6 Static Fusion

The previously described fusion techniques all provide global estimates which are optimal in the linear minimum variance (LMV) sense conditioned on the same global measurement set In the decentralized fusion case local LMV estimates ($\hat{x}_i = E[x/Y_i]$) are used to form a fused LMV estimate ($\hat{\mathbf{x}} = E[x/Y_1, ..., Y_p]$). An often used simplified alternative, referred to herein as static fusion, is to form local LMV estimates ($\hat{x}_i = E[x/Y_i]$) then resort to an alternative optimality criterion in forming the fused estimate [34-35]. This fusion of the local estimates is arrived at by statically minimizing the square of the estimation error, giving rise a fused estimate as [33] (see figure 8)

$$\hat{\hat{\mathbf{x}}}(k+1|k) = \left\{\sum_{i=1}^{p} P_i^{-1}(k+1|k)\right\}^{-1} \left\{\sum_{i=1}^{p}\left[P_i^{-1}(k+1|k)\hat{x}_i(k+1|k)\right]\right\}$$

The resulting decrease in accuracy of the static fusion methodology over that of the LMV approach has been noted in [34] and explained in [35].

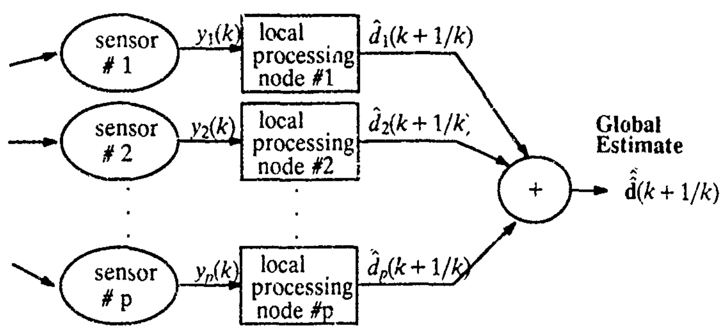

Figure 8 Static information fusion (SIF) of local estimates.

4.7 A Comparison of Fusion Techniques

A point form comparison of the preceding fusion techniques is based on the following categories:

i) Level of fault tolerance, *ii)* computational burden, *iii)* amount of inherent parallelism, *iv)* the ability to compensate for manoeuvring targets, *v)* the ability to cope with spatially uncollocated sensors, *vi)* communications requirement, *vi)* the ability to handle multiple information rates, and *vii)* the ability to fuse active and passive sensors.

filter	Fault Tolerance	Compute Burden	Inherent Parallelism	Manoeuvre Compensation	Uncollocated Sensors	Multiple Data rates	Active & Passive
CEF	low	moderate	low	difficult	moderate	difficult	difficult
CMF	low	low	low	moderate	difficult	difficult	difficult
SF	low	high	low	moderate	difficult	difficult	difficult
GDF	moderate	high	moderate	moderate	simple	moderate	difficult
DIF	high	moderate	high	simple	simple	simple	moderate
SIF	high	low	high	simple	simple	simple	simple

Based on the above chart the static information type fusion (SIF) technique is the favoured choice, but due to its slight reduction in accuracy (about 5-10% [34]) the decentralized information type fusion (DIF) technique may be favoured. It should be also noted that it is very simple to go from DIF to SIF and vice versa, and thus the switch from DIF to SIF can be made when computational burden takes precedence.

5. A HYBRID MULTI-SENSOR MULTI-TARGET TRACKER

In the case of the multi-sensor multi-target (MSMT) tracking problem two architectures have predominated most published works [36]. One of these architectures is the sensor level tracker which utilizes local single-sensor multi-target (SSMT) trackers.

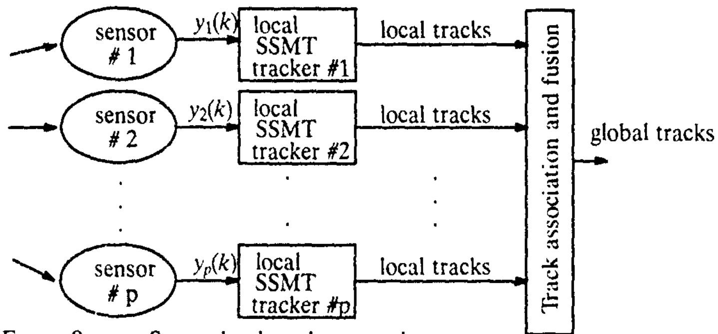

Figure 9 Sensor level tracking topology.

The primary alternative architecture is the so-called central level tracking approach

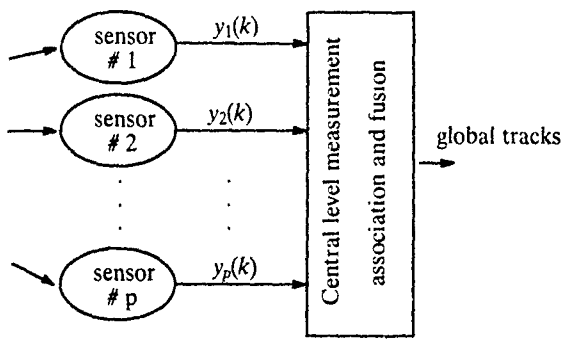

Figure 10 Central level tracking topology.

The primary advantage of the sensor level MSMT tracking topology is its fault tolerance and high level of inherent parallelism, which allows local SSMT trackers to be tailored specifically for each sensor The almost exclusive use of static fusion techniques to perform the track-to-track fusion results in a corresponding slight decrease in tracking accuracy. Howevei, non-static fusion techniques such an the DIF technique can be utilized to remedy that shortcoming. The central level tracking topology typically allows improved associations and thus more accurate global track formation.

A hybrid technique which takes advantage of the decentralized sensor level tracking technique's virtues while utilizing measurements (or measurement sequences corresponding to tracks) to perform track-to-track associations retains the advantages of both approaches This approach is illustrated in figure 11 below.

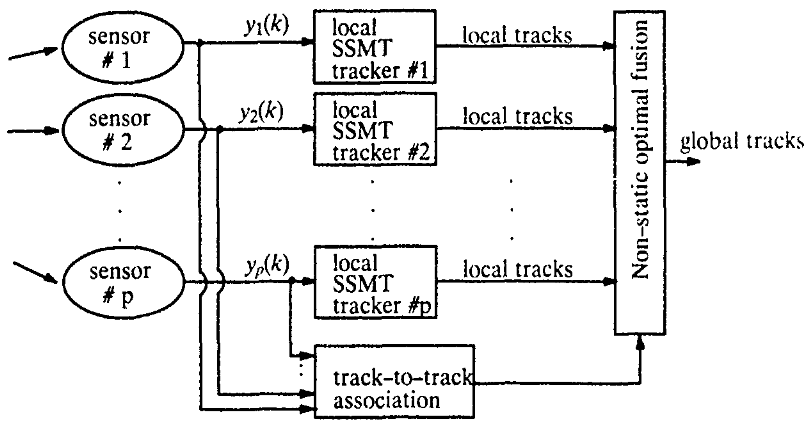

Figure 11 A decentralized hybrid MSMT tracker

6. SUMMARY

The information processing topology required to implement these fusion strategies dramatically influences the real-world applicability of a given fusion technique. It is also desirable that the processing environment be capable of facilitating the considerations itemized earlier in section 4.7. Specifically, it is possible to construct a solution to the sensor fusion problem within the framework of the previously developed sensor and target dynamic models [4], which is inherently well suited to a distributed (decentralized) processing structure, thereby allowing processing to be carried out simultaneously with local processing resources (parallel computing).

The centralized alternative is often simpler to implement [37], while the decentralized procedure requires a hierarchy in the fusion procedure to allow local processors to perform constructive operations. Minimal communications between local nodes is necessary if real parallel processing is to be achieved. If the solution to the sensor fusion problem can be suitably formulated, then the decentralized information type fusion (DIF) processing

topology can be employed to offer a high level of fault tolerance, and the possibility of real time operation.

The direct extension of the DIF (or SIF) to the MSMT problem is demonstrated by the hybrid MSMT tracker. The high level of fault tolerance is complemented by the measurement level track-to-track association capability. This association can be derived using previously established elliptical or rectangular gating techniques (pointwise associations). Alternatively, measurement sequences corresponding to local tracks can be associated using more sophisticated methods such as Volterra kernel analysis (sequence associations). The latter techniques are capable of providing improved association by.

i) Accounting for higher order moments
ii) Dispensing with linearized measurement and target motion models
iii) Accounting for serial cross-correlation.

In the event that the the independently operating track-to-track association processor fails, a back-up track-to-track association procedure can be performed using conventional sensor level tracking techniques.

At present, the development of a modular structured software environment for the comparative evaluation of multi-sensor multi-target tracking techniques in clutter with false alarms, is being undertaken.

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THE APPLICABILITY OF AI FOR THE DEFENCE OF SMALL SHIPS AGAINST AIR ATTACK

by O. Kandyba *

TABLE OF CONTENTS

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ABSTRACT

1. The key attributes of the ship's air defence problem are reviewed in context of a NAAWS ship and mapped onto available AI techniques. Some of the main benefits of using AI vs procedural techniques are presented. From this, a list of processes is derived showing the best candidates for implementation using AI.

2. It is seen that naval AAW is primarily a distributed real-time AI problem which is fundamentally different from non-real time AI. Currently available AI tools, techniques and processors may not be capable of satisfying the real-time performance requirements of large AI-based systems. A case is made for new parallel processor architectures which are capable of flexible high speed inferencing in hardware.

3. We contend that at present, the development of mission-critical systems using AI technology is both difficult and costly because in the military context, a validated AI technology base does not yet exist. Consequently, to reap the substantial benefits of AI, NATO needs to make a major investment in the development of this technology base. Several constructive suggestions are made in this regard.

1 INTRODUCTION

4. In 1989, Thomson-CSF Systems Canada Inc was awarded a contract by DREV on behalf of the NAAWS PMO to investigate the applicability of artificial intelligence (AI) to naval anti-air warfare (AAW). This paper presents some of the key findings of this study with the intention of providing a realistic assessment of this exciting technology in context of the system development process.

5. The short duration of naval anti-air engagements, the lethality of airborne threats and the vulnerability of small ships have been well recognized from recent experiences in the Falklands War and in the Persian Gulf [deBa90][Hewi88]. Among the lessons learned is that in order to survive, a ship's crews must effectively manage their ship as well as its defensive and offensive assets.

6. In modern naval vessels the flood of data from numerous internal and external sensors is both a blessing and a curse. Clearly, it is indispensable as a means of perceiving events unfolding in the surrounding environment, and provides the basis for making command decisions. Yet in the midst of combat when the need for decisive and effective action is highest, too much unstructured or irrelevant data becomes extremely stressful and leads to cognitive overload. When this happens, the ability of the crew to function effectively is greatly diminished, often with lethal results. The problem is complicated by the use of electronic warfare (EW) weapons both by airborne threats as well as ownships, as this generates incomplete, misleading or inconsistent information with which the crew must cope, and often places restrictions on how hard and soft kill weapons may be used in combination.

7. Therefore, one major thrust of modern naval combat system design is to reduce the load on the crew by automating the low level decision making in such a way that command teams will be presented with information which is timely, reasonably complete, and relevant to making command decisions. Clearly the low level decision making must be guided by a great deal of knowledge and expertise in ship's systems and weapons, various threat characteristics, and AAW tactics. This requirement poses a significant technical challenge to system developers.

8. During the last two decades, major advances have been made within the AI research community in the development of techniques to codify various types of knowledge and then use them to reason about real-world problems. This was accompanied by the development of various development tools such as advanced programming languages as well as hardware architectures which support the direct processing of knowledge. Therefore, as a technology, AI is emerging from the laboratory and has great apparent potential. For developers of advanced systems it holds the promise of being able to embed within them highly intelligent reasoning processes with capabilities which previously were characteristic of living human experts. Moreover, being computer-based, these reasoning processes are immune to cognitive overload, fatigue, inattention, inconsistent actions, outright mistakes, and other human failings. Systems which make significant use of AI technology are called knowledge based systems (KBSs).

9. Therefore, with respect to the effective management of a ship's defensive and offensive assets against air attack, AI technology appears quite attractive in its potential to reliably perform many of the reasoning tasks previously done by human operators. In exploring this further we will first examine the general benefits which AI holds for advanced system developers, and then consider the question of applicability to the naval AAW problem. Finally we will examine the actual feasibility of developing a naval AAW system in context of the system development life cycle.

2 THE BENEFITS OF AI

10. We first need to examine the fundamental question of "Why should one in the development of mission-critical systems, use a new and potentially risky programming technology when existing technologies may be perfectly adequate". We support the general principle that if indeed they are adequate, then clearly developers should stick to the tried and proven. However it is generally accepted that the use of AI yields several important benefits which in our view outweigh many of its perceived disadvantages:

1) **More reliable mapping between the real world and the software world.** In conventionally coded systems, all real world objects and their interrelationships (i.e. knowledge) are represented as collections of variables, flags, parameters, etc. The mapping to the software world can therefore become quite convoluted, requiring very strong discipline, organization and skill on the part of the software engineers. At some point we can expect to reach an intrinsic limit in the ability of software developers to comprehend and deal with complexity. In contrast, within KBSs the expressive power of the knowledge representation techniques allows knowledge to be represented at a high level of abstraction which is much closer to the way in which humans perceive the world. This leads to economy and clarity of representation, reduced numbers of software objects, all of which reduce system complexity. This in turn can reduce development time, increase reliability and maintenance costs.

2) **Decoupling between knowledge and control processes.** In procedurally coded software, the knowledge and control processes are inextricably intertwined in the structure of the code. This certainly is responsible for many of the difficulties associated with producing and maintaining high reliability software. In KBSs, on the other hand, the knowledge base is completely independent from the control processes which are resident in the inference engine software. Consequently both of these can be developed and validated separately and then combined in a single KBS application. (This software architecture has resulted in the appearance of a large number of expert system shells which contain everything but the knowledge base, the production of which is completely dependent upon the given application and is therefore the responsibility of the purchaser).

3) **System extensibility yielding improved maintainability.** Extensibility is defined as the ability to significantly extend the capabilities of a system without introducing significant disruptive changes to the system. In KBSs the decoupling between the knowledge base and the inference engine greatly improves system extensibility. In order to give a KBS additional reasoning capabilities, all that is required in most cases is a modification of its knowledge base while leaving the control processes in the inference engine intact. In procedurally coded software, equivalent changes would require a major software rewrite with the attendant costs and risks.

4) **Flexibility and robustness** in KBSs is defined as the ability to sensibly handle situations for which the system was not explicitly designed. In conventionally coded systems, the software designers must foresee and cater for wide range of eventualities which the system must handle. Clearly there is a total dependence on the experience, foresight and imagination of the personnel involved. As the system is modified to handle ever increasing numbers of specific operational scenarios, both the complexity and size of the software will increase. Even with highly disciplined modern software engineering practices, such systems may become unmaintainable.

   In contrast, KBSs are implemented on a high level of abstraction. Their knowledge bases can be structured to handle multiple layers of issues on the appropriate level. [Wiel87]. Certainty management schemes can be

introduced to handle uncertain or missing data and to propagate its effects throughout the reasoning process. Knowledge-driven classification of situations can allow KBSs to provide sensible or useful solutions even when the input data or situation does not exactly match some predefined stereotype. Consequently, without the developer having to provide explicitly for them, KBSs can exhibit good operational robustness over a broad range of situations. Since flexibility and robustness do not necessarily imply a major increase in the complexity or size of the system, this comprises a major advantage over the use of conventional software technologies.

5) **Ability to handle ill-defined problems** is an important requirement in many mission-critical systems. Conventionally coded systems are comprised of clearly defined processes and algorithms which are meant to handle specific data sets or situations. When poorly defined situations are encountered, they are usually unable to handle them. On the other hand, humans routinely handle unusual situations, drawing upon diffuse high level knowledge, experience, rules of thumb, iteration techniques, or simply make judgement calls. These help to derive some kind of solution despite the initial obstacles. Since KBSs attempt to capture human knowledge, in principle they have the potential of duplicating even this sphere of human judgement. However, it is recognized that this particular area is still a research area.

6) **Dissemination of expertise** is a highly important attribute of KBSs somewhat related to the capture of human knowledge. Like any other software, electronic copies of KBSs can be widely distributed to provide judgement in some domain when and where needed. Moreover, since knowledge bases are separate from the remainder of the system, they are portable to other remote systems possessing the same inference engines. In terms of naval AAW, doctrinal knowledge or experiential knowledge of human operators and Tactical Action Officers (TAOs) can be codified, combined, made consistent, and then distributed among all combat systems in the fleet. When suitably integrated with the previously deployed knowledge bases, the new knowledge can potentially improve the operational effectiveness of all units receiving these updates. Clearly this would be impossible with conventionally coded software.

7) **Fast prototyping.** The KBS development tools currently available on the market yield the benefit of fast prototyping of applications which may not necessarily be related to AI. In order to establish the viability of a given technical approach, it is often desirable to test some initial ideas and then commit to a specific solution. Because of their interactivity, powerful debugging tools and libraries of utilities, sophisticated development environments can be particularly effective in getting an application up and running very quickly. This is particularly true if the application involves a significant amount of logic or a complex man-machine interface. Such environments typically support hooks to a variety of procedural languages allowing the developer to produce hybrid KB and procedural code systems. In contrast, few development environments for conventional procedural code support such flexibility and degree of interactivity.

11. We see that the use of AI technology does indeed yield significant benefits to advanced system developers. At the same time it carries with it some risks which will be discussed when we consider life cycle issues.

3 HOW APPLICABLE IS AI TO NAVAL AAW?

12. This question is best answered by examining a specific ship's combat system architecture. The NAAWS conceptual block diagram shown in Figure 3.1 is quite representative of modern combat system concepts, and was used as a focus of the Thomson Systems study. Since the NAAWS ship's sensors and weapons are a given, the study concentrated on the Core functions. In Figure 3.2 they have been shown as a functional tree which was decomposed down to level 2. The investigation consisted of two stages:

1) The identification of NAAWS subsystems which are good candidates for implementation using AI technology; and

2) An examination of the system life cycle issues which have a strong bearing on the successful implementation of AI-based naval AAW systems.

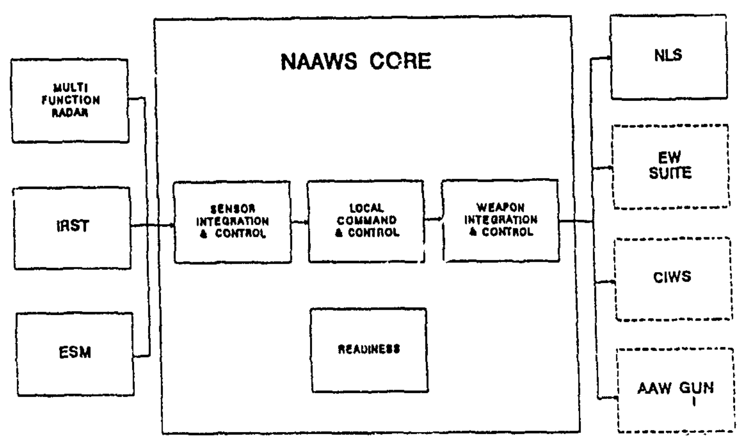

Figure 3.1: NAAWS CONCEPTUAL BLOCK DIAGRAM

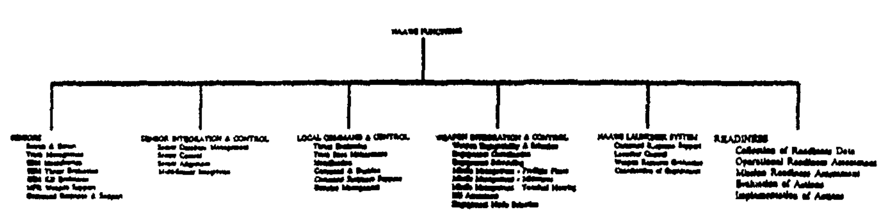

Figure 3.2: HIERARCHY OF NAAWS FUNCTIONS

13. Figure 3.3 depicts the methodology used during the first stage of the study. Each of the NAAWS functions was examined to quickly weed out unsuitable applications on the basis of inappropriate problem types and high level system requirements. For each of the surviving functions the characteristics of the required development tools were established by considering appropriate knowledge representation forms, inference engine types and inference control strategies. The detailed assessments of each NAAWS function were recorded in tabular format and a sample for one NAAWS function can be found in Annex A. On the basis of these tables a final decision was made whether a given function was potentially a good candidate for implementation using AI technology. Finally, a survey was conducted of currently available AI development tools as a precursor to the selection of a recommended toolset [Bein89].

14. As a result of the stage 1 analysis process, Table 3.1 below lists the NAAWS functions which could potentially benefit from implementation using AI. [Kand89A] contains a detailed discussion for the underlying reasons for these selections. The study concluded that this list would probably have to be studied further and prioritised in order to reduce development risks and maximise the benefits. The remaining functions found in Figure 3.2 were viewed as candidates for procedural software implementations.

15. Because of the large number of NAAWS functions appearing in Table 3.1 above and of course the underlying reasons, we conclude that in general AI appears to be applicable to the development of naval AAW systems.

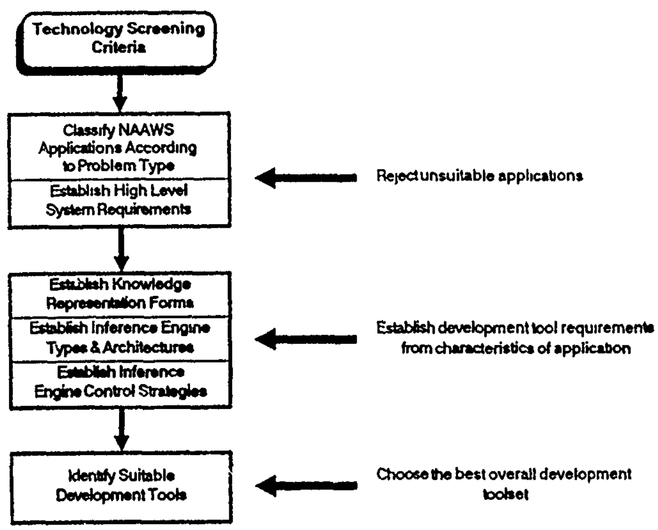

Figure 3.3: SCREENING METHODOLOGY CONSISTS OF MULTIPLE LAYERS OF CRITERIA

TABLE 3.1: NAAWS FUNCTIONS POTENTIALLY BENEFITING FROM AI TECHNOLOGY

Sensor Integration & Control
- Sensor Control
- Multi-Sensor Integration

Local Command & Control
- Threat Evaluation
- Identification
- Command & Decision

Weapon Integration & Control
- Weapon Engageability & Selection
- Engagement Coordination
- Engagement Scheduling
- Kill Assessment

NAAWS Launcher System
- Launcher Control
- Weapon Resource Evaluation

Readiness
- Collection of Readiness Data
- Operation Readiness Assessment
- Mission Readiness Assessment
- Evaluation of Actions
- Implementation of Actions

4 BUT IS IT FEASIBLE?

16. Unfortunately, establishing the applicability of AI to naval AAW is a rather superficial finding which can make no claims about the feasibility of actually doing so. This requires an examination in context of the system life cycle of several critical interrelated issues such as the AI development toolset and the adequacy of system performance on the available computing platforms.

4.1 KBS Development Life Cycle

17. Of necessity, the life cycle of pure KBSs is very much different from DoD-STD-2167 or 2167A which are used for mission-critical procedural software development. Because of the way in which KBSs are developed, these existing models are totally unsuitable. As shown in Figure 4.1, KBS developments take place in two separate and distinct Phases: Prototyping and Delivery.

18. During the Prototyping Phase, the system is iteratively evolved in a rich development environment which is highly conducive to experimentation. The objective is to progressively create and validate the application knowledge base by expanding its capabilities in a series of incremental steps. This implies that the development must go through several passes around a loop consisting of Requirements, Design, and Build & Test stages. The inevitable logic faults must be corrected through modification and subsequent exhaustive testing of the system until it operates correctly. Then the developers face the task of devising a suitable strategy to deliver the system onto the target platform. We stress the need for a powerful Prototyping Phase toolset to boost the programmers' and knowledge engineers' productivity by supporting flexible experimentation and debugging.

19. The Delivery Phase consists of carefully reimplementing the prototyped KBS in a suitable procedural language hosted by the target machine such as C or Ada. This process is virtually identical to conventional software developments: Requirements, Design, Build, Test, Verify & Validate, etc. The chief difference lies in the fact that in order to tune the performance of the delivered system, developers may have to go around an iteration loop to the Design step from the Testing or Verify & Validate steps.

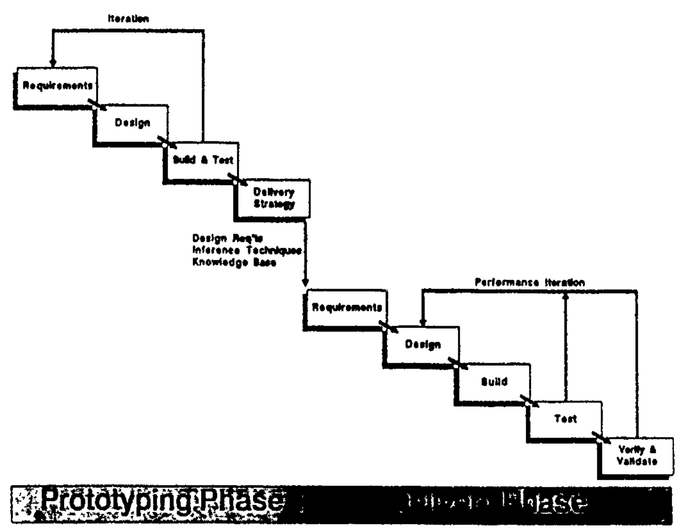

Figure 4.1: **KBS DEVELOPMENT IS AN ITERATIVE TWO PHASE PROCESS**

20. Clearly, the system must be thoroughly retested to ensure that it still works correctly. Unfortunately, in order to maximise system performance, in its delivered form the system will no longer contain the powerful features which supported the debugging process during the prototyping phase. Consequently developers are left with a difficult laborious task which must be done using conventional methods with the help of suitable CASE tools. Under these conditions, the productivity advantages of using AI programming environments will be lost. This is especially true when the system needs to be extended or somehow modified in the future. Either a return to the prototyping environment is needed and followed by recoding, or the delivered system must be modified with the attendant risks.

21. The Thomson study found that with very few exceptions, commercially available development tools are unable to facilitate delivery of prototyped systems to standard military compu'.ng platforms. The notable exception was the ART environment which will soon be able to automatically generate Ada delivery code exactly duplicating the function of the prototyped system.

22. Another finding of the study was that most advanced systems will in all likelihood be synergistic hybrids of knowledge-based and procedural functions. Consequently, a new life cycle model will be required to support such system developments. In all likelihood, it will feature two parallel development streams which recognise the optimum development style of each type of software, and with suitable cross-links between them for purposes of integration and testing.

4.2 Development Toolset Issues

23. After the Thomson study completed the examination of the various NAAWS functions, the summary of findings such as those shown in Annex A, showed that virtually all known knowledge representation, inferencing techniques and control strategies will be required in the implementation of the list of NAAWS functions shown in Table 3.1. Assuming that a single organization is tasked with the job of prototyping them, then a full capability integrated toolset is indicated with features such as:

* Highly interactive man-machine interfaces;
* A full suite of knowledge representation and inferencing techniques;
* Flexibility to customize/extend inferencing and control mechanisms;
* Easy access to various symbolic as well as procedural programming languages;
* A large suite of utilities supporting the knowledge engineering, and configuration control processes;
* A powerful interactive debugger;
* Support for the generation of all software documentation;
* Etc.

24. Such integrated toolsets should really be considered as "environments". Typical examples of these are KEE, ART, NEXPERT and JOSHUA. These are quite expensive, but in a large program such as NAAWS, once the personnel training was completed, they would more than pay for themselves through enhanced programmer productivity during the Prototyping Phase.

25. One may argue that if the development task was properly partitioned, then a more modest development environment featuring a subset of the above capabilities could be sufficient for some groups of functions. However, development environment heterogeneity may cause problems with system integration because it is not immediately obvious in which development environment to assemble the outputs of parallel developments. Moreover, the individual KBS applications may not be portable to the chosen integration environment. Finally, multiple heterogeneous environments can create a nightmare in the maintenance of delivered systems due to increased personnel training requirements.

26. Therefore, as a guideline the Thomson study concluded that in parallelised developments of major AI-based systems, a single environment containing a superset of the required features should be chosen. Moreover, for the development of mission-critical systems, it is advisable that NATO choose a standard development environment or toolset which fully supports the requirements of the new life cycle model mentioned above, with delivery targeted at specific NATO standard computing platforms.

4.3 Real-Time Issues in AI-Based AAW Systems

27. Initially, AI techniques were applied to problem domains where the data were relatively static and time-critical responses were not required. However, if we wish to use AI for the development of the next generation of naval AAW systems, then we must consider the implications of the key characteristics of the application. Clearly, all naval AAW systems such as the NAAWS are real-time (or time constrained) distributed processing systems. Consequently, AAW KBSs must satisfy the following requirements which depends on the capabilities of the development tools used:

Asynchronous events. An AAW system must be capable of responding to asynchronous or unscheduled events as they occur by interrupting its current work and processing new data according to its importance [Laff88] (e.g. the sudden appearance of a sub-launched anti-ship missile). Most of the current KBSs do not allow an interruption of an inference cycle.

Guaranteed response times. The system must be able to produce an acceptable response within a finite time limit. Some experimental systems were able to meet response time requirements by providing responses with various degrees of certainty or completeness.

High performance. The system must perform complex decision-making based on a massive stream of incoming data in a timely manner. In naval AAW, response times need to be in the order of 0.20 sec. Given the latency of the data bus connecting the distributed computing assets and the amount of inferencing to be done at each stage, the performance of the individual processors becomes a crucial issue. KBSs do not execute very efficiently in a general purpose Von Neumann monoprocessor.

Optimal use of resources. The system should make optimal use of resources such as CPU, memory, and communication bandwidth. For example, in a real-time system an interpreted knowledge base would be unacceptable because it would unnecessarily burden the processor. A compiled version would perform far better. Also, features of the development environment which are not strictly necessary should be excluded from the delivered system. Many KBS development environments do not support any tailoring of the delivered system.

Focus of attention. The real-time KBS should service critical events as they occur, and reallocate system resources as required. For example the occurrence of a high priority event may trigger the use of a different knowledge base which is more appropriate for the problem conditions.

Continuous operation. The system must be capable of operating over long periods of time despite multiple hardware failures. This requires that the

system monitor its status and intelligently reconfigure its assets to meet the critical requirements of the mission as long as possible.

Temporal reasoning. In AAW, time is a highly important resource in all aspects of decision making. As part of the planning process, the system must be capable of reasoning about past, current and future events and their sequencing.

Concurrency/distribution. Generally speaking, higher performance can be achieved through a higher degree of parallelism by partitioning large tasks into sets of smaller subtasks which can run on separate processors. Clearly, in multiple KBSs, co-operative behaviour must be ensured through careful design.

Non-Monotonicity. AAW systems are characterized by the transient nature of their input data. The validity of incoming data may change with time. Also facts deduced by the system may become invalidated by the occurrence of new events (e.g. the target which was thought to be a hostile is a battle-damaged friendly aircraft with an intermittent IFF). In both cases the system requires the ability for non-monotonic reasoning to backtrack and revise some of its conclusions.

Integration with procedural components. Procedural code will inevitably be used to implement much of the low level algorithmic processing found in real-time systems. Means must be provided to integrate the knowledge-based and procedurally coded components of the system into a synergistic whole where the strengths of both technologies can be used effectively to maximise the performance of the system.

28. The development of an actual AAW system requires a development tool with all the above attributes. However, from the development tools survey carried out in the Thomson Systems study, the overwhelming majority of the available development tools were not able to satisfy more than a few of the above requirements [Bein89]. More important, few tools allowed the developer customise them in order to extend their capabilities. In short, the currently available tools are inadequate for the task.

4.4 The _uest for Performance

29. Because of the short response times which are required for naval AAW systems, their component KBSs must be designed for maximum performance. Traditionally, in the development of time-critical applications, software developers use several techniques in combination to achieve their performance objectives:

* The fastest possible language plus very efficient code;
* More powerful processors and special purpose hardware;
* Computational parallelism;
* Clever analytical approaches to reduce the problem;
* Multi-levelled vectored interrupts;
* Etc.

30. These approaches certainly apply to the development of KBSs. However there is the additional complication that the inferencing process is not nearly predictable as procedural code. This is largely due to the decoupling between the knowledge base and the inference engine, and makes it virtually impossible to predict their performance and determine if a given design will be fast enough. Consequently developers will discover performance inadequacies only during advanced stages of prototyping and during the development of the delivery system. This stresses the need for an iterative development approach supported by a powerful toolset.

31. Estimation of system performance by comparison with similar existing systems is equally difficult because of the variability in the end results introduced by implementation features. Without a full disclosure of the processor characteristics, inferencing technique, ' ːuristics used, characteristics and structuring of the knowledge base, the role of procedural code elements, etc. it is virtually impossible to make extrapolations to a different system. All that one can say is: "So and so successfully built a similar system and I probably can make my system work in the end!" However this can hardly be considered to be a controlled engineering approach.

32. There is a dearth of sufficiently well documented KBSs in the literature which would allow new system developers to make intelligent extrapolations. There are few meaningful published benchmarks on existing systems. In short, in the area of KBSs, the defence contractor community lacks hard engineering design points from which to extrapolate to new systems.

33. The Thomson study also considered whether some system performance estimates could be obtained from measurements of the number of machine instructions per logical inference. In the case of the HEXSCON, a rule-based expert system shell [Wrig86], it was estimated that 143 instructions were needed per inference. Assuming that this is a typical value the graph shown in Figure 4.2 was derived. It shows response times vs numbers of rules fired for processors with a computational power ranging from 1 to 20 MIPS. Given a specific processor power and an estimate of the number of rules fired on average, one can ostensibly determine the system response time. If the answer is too large then presumably some of the performance maximization techniques described above could be applied. This however is a trap because the number of machine instructions per logical inference depend on factors such as:

* The architecture of the processor chip;
* The efficiency of the KBS inference engine;
* The average number of antecedent conditions in the rules;
* The mix of knowledge representation types;
* The execution of any procedural code which was part of the original application;
* The efficiency of the compiler which produced the run-time module;
* Etc.

34. Consequently extrapolations of any kind must be treated with extreme caution because the results may be uncertain up to half an order of magnitude.

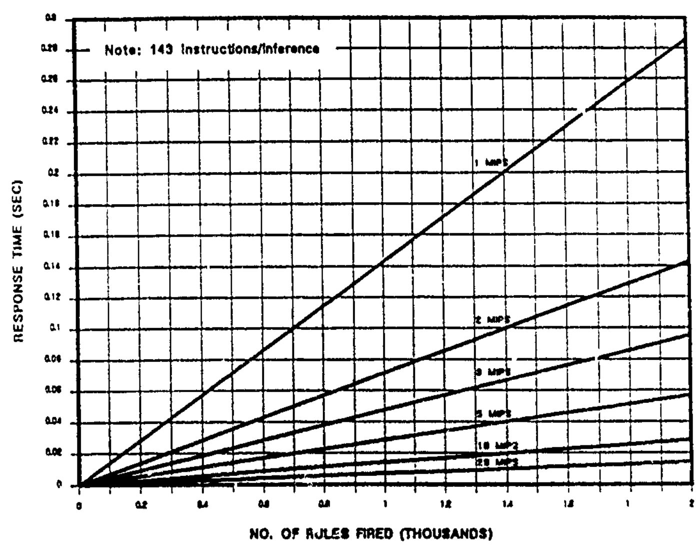

Figure 4.2: RESPONSE TIME OF A RULE-BASED E.S. VS. NO OF RULES

Instead, we propose to look at the potential inferencing rates from currently available processor technologies:

* A single conventional processor: the HEXSCON expert system running on an Intel 8086 [Wrig86];
* A fine-grained multi-processor: The Production System Machine with 32 processors [Gupt86];
* A special purpose processor supporting Prolog [Odet87];
* A coarse-grained multi-processor: Expert-5 running two MC68000 processors [Park98];
* A hardware inference engine: AT&T fuzzy inference chip [Toga86].

35. The comparative graph is shown in Figure 4.3 below. Now let us examine how the NAAWS case would fare with these processors. Say NAAWS contains 10,000 rules, 20% of which would be triggered in the course of processing a typical sweep of new data. Assuming an inference rate of 20,000 rules per second, it would take the system about 0.1 seconds to perform the necessary reasoning. It is evident that this performance level, although fast, may become inadequate if one considers that the system response must account for procedural functions, communications overheads, as well as all other latencies and bottlenecks in the reaction pipeline.

36. It is important to note that the latter applies to the current generation of anti-ship missiles. With supersonic missiles or hypervelocity projectiles, the response time would really have to be possibly reduced by more than one order of magnitude. Therefore in the near future, developers should aim for at least 200,000 logical inferences per second from computing platforms executing AAW AI applications.

4.4.1 Parallelism to the Rescue

37. According to Shaw, the majority of the processing cycles used in inferencing are for performing various types of pattern matching [Shaw87]. For example:

* In rule-based systems the matching of antecedent conditions to determine what rules to trigger next;
* In frame based systems the comparison of frames;
* In classical logic systems, the matching of strings of symbols;
* Etc.

38. Single processor Von Neumann machines are notoriously slow and inefficient at pattern matching and when applied to execute KBSs, the performance of the system cannot meet very stringent real-time performance requirements. However, parallel processor architectures are ideally suited for AI pattern matching tasks, and also have an important role to play in procedural algorithmic processing. In KBS applications, architecture flexibility and scaleability are also very important requirements because of the wide variety of application tasks which the processor will be expected to perform.

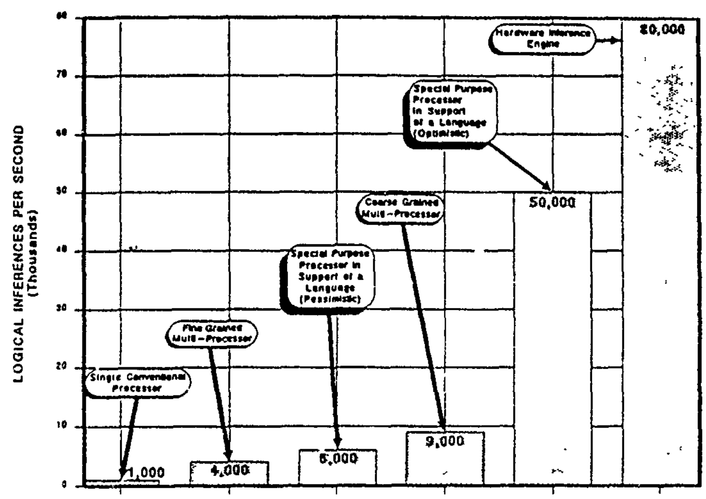

Figure 4.3: THE PERFORMANCE OF VARIOUS TECHNOLOGIES & ARCHITECTURES

39. Two architectures known to the author appear to be able satisfy these requirements. Shaw's NON-VON machine was one of the first to explore fine-grained parallelism as applied to a wide variety of AI applications ranging from machine vision to all of the common forms of inferencing [Shaw87]. The architecture, which featured custom VLSI processors arranged as a programmable active memory, was able to demonstrate very large improvements in inferencing performance. Unfortunately, to the best of the author's knowledge, the NON-VON machine was never meant to be commercialized and remains as a research tool.

40. A second and more interesting parallel processor machine called the PADMAVATI is currently in an advanced stage of testing at Thomson-CSF in France. The machine was specially developed under the European Esprit Program to explore computational parallelism in image processing, speech recognition, and other AI applications.

41. This machine consists of a VMEbus boardset based on the Inmos T800 processor and a custom VLSI delta switch chip. As shown in Figure 4.4, the PADMAVATI acts as a special purpose co-processor for a general purpose master computer. The normal Transputer E-W links are used to individually program and control a ring of Transputers. The programmable delta network in the middle of the ring allows any Transputer at runtime to quickly connect to any other Transputer in the ring and exchange data. The PADMAVATI currently executes Le LISP and C, with Ada to be available in the near future.

42. The unique thing about the PADMAVATI architecture is its ability to be scaled to suit the performance requirements of the application. The basic processor board has 16 Transputers for a total of approximately 2.1 million LIPS of inferencing power. Multiple boards can be daisy chained up to a maximum of 256 Transputers yielding 34.1 million LIPS.

43. We contend that an architecture like the PADMAVATI is ideally suited to the challenges posed by the naval AAW task. Because it can execute signal processing, general computation as well as AI applications, it can be treated as a general purpose co-processor in the context of a combat system architecture.

44. Moreover, with the uncertainties in the amount of inferencing power actually required by an AAW system, the architecture can be easily scaled up at any time and without penalty, to bring the necessary power to bear on the problem. Indeed the capabilities of the PADMAVATI or its successors are such that it should be very seriously investigated by the appropriate technical authorities within NATO.

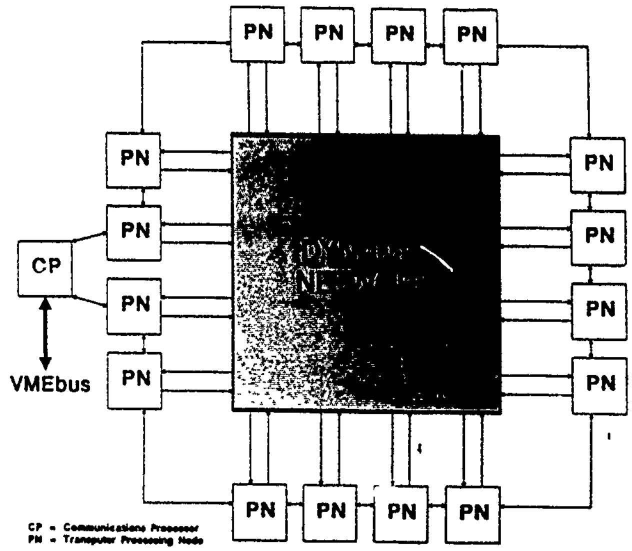

Figure 4.4: ARCHITECTURE OF THE PADMAVATI PROCESSOR

5 CONCLUSIONS & SUGGESTIONS

45. From the above, we conclude that AI certainly is very much applicable to the development of advanced naval AAW systems but the task is barely feasible at the present time. Any AI-based military systems which will be deployed in the very near future will out of necessity be hand crafted, and will be far more expensive and unreliable than the an equivalent amount of procedural code. The chief reason for this is that the necessary validated technology base is not yet available. Specifically, the development environments currently available do not have a sufficiently complete set of capabilities to support the entire development process for military knowledge based systems including delivery to military platforms. More important, most of them do not support the features necessary to develop real-time KBSs. Consequently all of these must be added as custom features by system developers at increased cost.

46. In order to reap the numerous benefits of AI technology, the various defence organizations within NATO need to make an investment in the development of a validated technology base for the development of mission systems based on AI. This means establishing a new system development model to replace DoD-STD-2167A, which recognises the requirements of developing software systems which are hybrids of AI and procedural code. Also, since commercial tool developers currently have little incentive to develop the tools with the capabilities required for military real-time applications, NATO defence organisations may have to jointly sponsor the development of their own standard, validated development environment. Clearly , this KBS Real-Time Development Environment (KRDE) would have a far wider applicability than AAW. Ideally it should have the following features:

* A good graphical man-machine interface;
* Contain a library of numerous standard knowledge representation forms and supporting inference engines;
* Be highly modular and support the addition of new functions, tools and capabilities as required;
* Allow prototyping and experimentation on the LISP level;
* Allow easy interfacing with a variety of procedural languages;
* Provide direct support for real-time KBS development and testing;
* Provide various knowledge engineering tools supporting the acquisition and maintenance of knowledge bases;
* Possess powerful debugging and testing utilities;
* Provide support for the management of the KBS development life cycle;
* Support the generation of all software documentation;
* Able to support special purpose hardware inference engines;
* Highly desirable to be able to select and cross-compile to several specific delivery languages.

47. If KRDE is developed in the Ada language, then it could be ported to any military platform which supports Ada, including the target platforms. KRDE would reduce training costs because programmers would always face the same environment wherever they worked. An additional benefit stemming from KRDE is that defense organizations would be able to ensure that KBSs would be developed in accordance with standard processes and methodologies, out of

validated building blocks, thereby greatly simplifying the system verification and validation problem.

48. We suggest that AI will not displace conventional procedural programming technology; merely supplement it in specific important areas. It should be treated as the next step in the evolution of computer languages. However, the various NATO defense organizations must come to terms with the fact that AI languages are unique yet necessary, and may in some specific areas displace Ada as the standard programming language.

49. Another important task is that of devising suitable techniques to verify and validate (V&V) real-time as well as non-real-time KBSs. This is a particularly thorny problem due to the decoupling of the knowledge base and the inference engine [Kand89B]. It is exacerbated by the lack of diagnostic facilities in almost every KBS delivery environment. However, without suitable procedures in place, KBSs can not be adequately tested before deployment. As such, lack of V&V procedures constitutes a major risk in applying AI technology in mission-critical systems.

50. Currently available computer hardware appears to be sufficient for KBSs dealing with present day threats. However they may not be able to cope with the next generation of faster, more maneuverable and intelligent threats operating in a heavy EW environment. These factors may reduce response times by one order of magnitude and require much more sophisticated reasoning. Consequently it is suggested that a new class of flexible, general purpose parallel processors, such as the PADMAVATI, which are capable of doing AI processing as well as procedural processing, be considered for inclusion into the NATO inventory. By current standards these may be considered overkill, but by the time that they are deployed, our ships will be facing the next generation of threats and may well require such high performance.

6 EPILOGUE

51. Since concluding the study on the role of AI in the naval AAW process, Thomson-CSF Systems Canada was awarded a contract by DREV to implement a proof-of-concept TEWA simulator system using AI technology. As such, it was an important step in the development of a validated technology base for AI-based AAW. The technical approach consisted of a synergistic fusion of procedural, AI and object-oriented programming technologies. The resulting system gives an unprecedented degree of flexibility in being able to experiment with TEWA concepts through a very powerful man-machine interface. The TEWA implemented consists of five co-operating expert systems responsible for different segments of the reasoning. Currently the project is nearing completion and Thomson Systems expects to report the results at the earliest possible opportunity.

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8 ABOUT THE AUTHOR

52. Mr. Oleh Kandyba holds a BSc in Engineering Physics ('67) from Queens University, Kingston, Ontario and an MEng in Systems Engineering ('90) specializing in AI from Carleton University. His main interests are in artificial intelligence, neural networks, system engineering, computer architectures, robotics, software engineering, and computer applications of holography. In AI he is working in distributed AI, especially in co-operating expert systems.

53. The work described in this paper was performed at Thomson-CSF Systems Canada Inc., Nepean, Ontario, Canada, under the leadership of Mr. Kandyba where he served as the Manager of Computer & Software Engineering. Mr. Kandyba was responsible for the emplacement of AI capabilities and other advanced technologies within the Company. Mr. Kandyba currently is a Systems Engineering Manager at MEL Defence Systems Ltd., Stittsville, Ontario, Canada.

ANNEX A: ASSESSMENTS OF NAAWS FUNCTIONS

1. This Annex contains an example of the NAAWS function assessment tables from [Kand89A]. These tables were used to determine whether a given function could indeed benefit from implementation with the help of AI technology, and what were the required characteristics of the toolset to be used in the implementation of each function.

Local Command & Control \ Application Type	Data Interpretation & Synthesis	Prediction	Diagnosis	Repair/ Treatment	Use Advisor	Instruction/ Training	Design/ Configuration	Monitoring	Control	Scheduling	[illegible]		Natural Language [illegible]
Threat Evaluation	X												
Track Base Maintenance													
Identification	X												
Command and [illegible]	X										X		
Command Response Support													
[illegible] Management													

Table 5-3A: Local Command & Control - Application Types

Local Command & Control \ System Reqts	Deep Knowledge	Experiential Knowledge	Assumptions Required	Uncertainty in Knowledge or Data	Algorithmic Components	Dynamic Data Creation/Deletion	High Data Rates	Time-Varying Data	Access to Databases	Standalone Operation	Embedded Operation	Operator Acceptable Speed of Execution	Fixed Execution Speed Required	Input/Output - Graphics	Input/Output - Text/Numeric
Threat Evaluation		X	X	X				X	X		X		X		X
Track Base Maintenance					X			X	X		X		X		X
Identification		X	X	X				X	X		X		X		X
Command and Decision		X	X	X				X	X		X		X		X
Command Response Support								X	X		X	X	X	X	X
Doctrine Management															
-															

Table 5-3B: Local Command & Control - System Requirements

Local Command & Control \ Knowledge Representation	Rules	Frames/Objects	Facts Object-Value	Facts Object-Attribute-Value	Facts - Developer Specified Sources	Developer defined Data Types	Developer-defined Relations	Pattern Matching	Temporal R	Procedures	Neural Networks		
Threat Evaluation	X	X							X	X			
Track Base Maintenance										X			
Identification	X	X	X						X	X	X		
Command and Decision	X	X	X					X	X	X			
Command Response Support		X											
Doctrine Management	X	X											

Table 5-3C: Local Command & Control - Knowledge Representation Techniques

Inference Engine / Local Command & Control	TECHNIQUES	Inheritance - Tool Defined	Inheritance - Developer Modifiable	Forward Reasoning Demons	Forward Chaining	Backward Chaining	Rule Iteration	Message Passing	Developer Extendable IE	ARCHITECTURES	Model Based Reasoning	Case Based Reasoning	Blackboards
Threat Evaluation		x		x	x	x	x	x					x
Track Base Maintenance													
Identification		x		x	x	x	x	x					x
Command and Decision		x		x	x	x	x	x				x	x
Command Response Support		x						x					
Doctrine Management													
–													

Table 5-3D: Local Command & Control - Inference Engine Types/KBS Architecture

Control Strategies / Local Command & Control	Meta Rules	Predefined Certainty Fact	Developer-defined Certainty Fact	Rule Salience	Fact Salience	Non Monotonic Reas (Viewpoints/Worlds)	Non Monotonic Reas (Dependency Based)	Non Monotonic Reas Variable Reset	Agenda Based Reasoning				
Threat Evaluation		x	x	x	x	x		x	x				
Track Base Maintenance													
Identification		x	x	x	x	x			x				
Command and Decision	x	x	x	x	x	x	x						
Command Response Support													
Doctrine Management													

Table 5-3E: Local Command & Control - Control Strategies

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14. Abstract:

The NA-25 is a shipborne Weapon Control System having additional capability of a mini Command and Control System and of an ESM Control System. It is based on:

- one single-operator dual-monitor multifunctional console
- a modular computer set employing standard data handling facilities
- a tracker system
- extended interface capabilities.

When connected with suitable data sources and users, the NA-25 can accomplish all the tasks asked to an advanced Combat System on small ships, saving space and manpower.
NA-25 is a product of the Naval Systems Consortium SELENIA-ELSAG.

NA-25

A

MULTIPURPOSE

WEAPON CONTROL SYSTEM

FOR

SHIPBORNE APPLICATION

FOREWORD

The NA-25 is an advanced modular weapon control system which mav incorporate an integral command and control capability thus providing a comprehensive AIO and weapon control capability in a single system configuration for small ships.

The NA-25 uses a powerful MARA multi-processor and a versatile display system which incorporates two high resolution colour monitors to present the raw radar and TV/IR video, the tactical situation and the supplementary information.

The fire control section of the NA-25 is provided with radar and optronic sensors and is capable of controlling weapons of medium calibre in the anti-aircraft and anti-surface roles as well as small calibre weapons in the CIWS role. Up to two guns of different calibres can be controlled at the same time.

The Fire Control Radar associated to the system is the ORION RTN-25, a fully coherent equipment which is characterized by anti-nodding, ECCM and anti-clutter features together with high tracking accuracy.

An electro-optic system (TV or optional IR/LASER) can be mounted on the radar director to enable firing assessment and to provide an alternative line-of-sight on the same target.

CONFIGURATIONS

Various system configurations can be provided to cope with different operational requirements; typical NA-25 configurations are:

a) FCS, incorporating one display console and implementing only the weapon control functions

b) SINGLE or TWO OPERATOR COMBAT SYSTEM, incorporating one or two display consoles and capable of performing fire control functions and to act as a small tactical system.

c) FCS INTEGRATED WITH IPN-S COMMAND AND CONTROL SYSTEM: in this case the NA-25 is not fitted with its own console but can be controlled by any display console of the common MAGICS display system.

The configuration described in this document is the FCS (point a) above.

DESIGN PHILOSOPHY

The design of the NA-25 FCS is intended to give a response to the operational requirements of Navies, both in terms of reaction capability against the most sophisticated threats, and in terms of integration, automation, easy handling and serviceability.
In more detail, the objectives envisaged in the design are the following:

a) defining a modular and flexible architecture capable of improving the FCS from a stand-alone configuration up to a small combat system incorporating command and control capabilities;

b) hardware standardization for minimizing the Life Cycle Cost;

c) man-to-machine interface standardization to cut down manning requirements;

d) ergonomic criteria optimization;

e) performances optimization in the use of medium calibre guns in anti-air firing and surface firing actions and, particularly, against low-level missile targets under stressing weather and electromagnetic environment conditions;

f) minimizing response times, both during the action and in setting-up the system.

The NA-25 FCS uses the MAGICS multi-functional display console which features:

. multi-sensor interface capability
. multi-sensor display capability on the same screen (mosaic)
. contemporary multi-mode presentation of the same sensor
. high resolution graphics and display
. two operationally interchangeable 20" high resolution colour monitors
. flexible configuration of the operator's desk
. standard interface to the application software (Display Management System)
. a MARA configurable multi-processor system as display processor.

The computer resources of the NA-25 FCS consist of two MARA multi-processor systems which feature:

. multi-processor computer power
. very high modularity which enables the use of a small range of hardware module types to construct systems with a wide range of processing power, memory and interface capacity
. single configurable operating system supporting both large and small hardware configurations
. strong support for fault detection, fault tolerance and maintainability
. separation of software into cooperating but protected functions
. high level system programming language, ADA.

The NA-25 FCS is fitted with the tracking radar ORION RTN-25 which operates in the J-band (formerly Ku). The main features of the radar are:

. high gain monopulse antenna with polarization twist
. coherent transmission chain with solid state frequency generators and TWT amplifier final stage
. two different waveforms in transmission
. antinodding capability
. frequency agility within the transmission band
. coherent multi-pole MTI for effective cancellation of moving clutter
. track-on jammer function
. extended set of anticlutter and anti-jamming features.

The acquisition pattern is optimized to meet the designation source accuracy; the subsequent target lock-on is automatic.

The tracking is automatic: it can be based either on the tracking radar data only or mixed using the TV angular data and the radar range, or based on the optronic sensors data if the laser range finder is installed.

The operational features of the NA-25 FCS and, in particular:

. engage process automation
. automatic evaluation of the threat to be counteracted
. availability of operation modes optimized as a function of the characteristic of the target
. efficiency of man-to-machine interaction.

allow to minimize the response time and to alleviate the operator's efforts.

SYSTEM CONFIGURATION

The typical NA-25 Fire Control System configuration includes:

a) Tracker Section consisting of

- Line of Sight (L.O.S.) including:
  - Servoed pedestal capable of mounting the tracking radar antenna and the electro-optic sensor suite (with a reference alignment sight);
  - ORION RTN-25 tracking radar antenna and associated R-F receiver box
  - Optronic sensor suite including a TV camera; (alternatively, TV/IR or IR/laser can be provided as option)

- Tracking radar ORION RTN 25

  The ORION RTN 25 is a pulse fire control radar operating in the Ku-band; it uses monopulse technique for tracking targets in angle.
  Functionally it consists of two receiver channels - one of which is limited in amplitude and performs target detection and acquisition functions; the second channel is linear and performs angular tracking functions.
  The radiated pulse is binary phase coded. Matched compression filters and anticlutter filters (MTI) are provided at the receive end of each channel.
  The transmitted frequency can be either fix or variable.

. Tracking MARA Computer

MARA (Modular Architecture for Real-Time Applications) is the name of a multiprocessor architecture developed by Selenia-Elsag. The MARA computer referred to in this document is the implementation of the MARA architecture oriented principally to real-time naval applications. However MARA has all the features of a general purpose computer and can be used in other applications.
MARA is based on the use of the 80X86 microprocessor series of Intel. Continued upgrading is implemented by Selenia-Elsag as new members of this series are produced and documented.
In the case of a multi-processor MARA up to eight microprocessors cana be connected to a common bus, called the nodal bus. This is electrically identical to the private busses of the single microprocessors, and memory units and I/O units can be inserted on it.

. Auxiliary Unit housing:

. Pedestal Servo Amplifier
. TV/IR video Tracker
. Power Distribution Unit

b) Gun Control Section consisting of

. Ballistic MARA Computer

c) Display Section

. One MAGICS display console configured as follows:

  . two raster scan high resolution colour monitors 20" (diagonal)
  . two video channels (one radar and one TV/IR)
  . graphic module
  . operator desk fitted with:

    . multifunctional keyboard
    . track-ball
    . joy-stick
    . alphanumeric keyboard
    . controls located on the monitors'side each monitor is fitted with 24 keys located on each side (12 on the left side and 12 on the right side); such keys are used for monitor control (e.g. brightness, video controls, etc.), and for operational functions. The meaning of each key is displayed in a dedicated area of the monitor.

. Presentation features

  1) Raw Video Presentation

  Radar signal selection is performed by means of manual controls located on the console: it is possible to select (via an external Radar Distribution Unit) 1 of 6 radar and 1 of 3 video for each radar. The following features are implemented:

  - PPI and A/R presentation of two different radars (one search and one tracker)
  - PPI and B presentation of the same radar

- display of the raw video only, mixed raw and synthetic video or synthetic video only
- display of the IFF video
- north or bow reference raw video presentation
- PPI presentation:
  . area: matrix of 960 x 960 pixels
  . range selection: any integer value in the range 0.5 to 1024 Km, DM, NM
  . off centre: in any point of the system area
  . range marks: selectable 0.25, 0.5, 1, 2, 5, 10, 20, 50 Km, DM or NM
- B presentation:
  . area: matrix 256 (range) x 512 (azimuth) pixels
  . amplitude: ± 4 Km in range and ± 5 degrees in angle
- A/R presentation:
  . matrix type A presentation (range, amplitude): 512 (X directin) x 256 (Y direction) pixels, or 256 x 128 pixels.
  . matrix type R presentation (expanded presentation of part of the track A): 512 (X direction) x 256 (Y direction) pixels, or 256 x 128 pixels
  . maximum range of the track A is 60 Km, DM, NM; the range of the track R is 2 to 4 Km, DM, NM.

2) TV presentation

. Matrix 586 x 780 pixels or the whole screen (960 x 1280)

3) Synthetic presentation

The console can generate and display the following synthetic information:

. symbols	used to display tracks, special points and marks
. lines	used to display vectors of variable length, bearings, maps, etc.
. curves	used to display circular areas or sectors
. alphanumeric characters	used, in association with the track symbols, to amplify information or, independently, to display other information

4) A/N tabular presentation

The console generates a number of tabular presentations of alphanumeric characters (ASCII) for supplementary information (e.g. TOTE area). The whole screen is used, and for a strip alongside the PPI presentation consisting of a matrix of 216 x 960 pixels.
The alphanumeric tabular presentation has the following features:

- management of cursor and standard ASCII editing functions
- scrolling
- blink
- background colours

SYSTEM OPERATION

The NA-25 Fire Control System can operate both under command and control supervision and as an autonomous system. All the operational functions, that is search, acquisition, tracking and firing, can be conducted either in fully automatic mode (under operator supervision) or under the direct control of the operator.

The NA-25 FCS is capable of performing the functions listed below:

- Autonomous search: by means of its own tracking radar which performs pre-programmed deck tilt-compensated search patterns both in azimuth and elevation; manual overriding with L.O.S. control by means of the joystick or optical search by means of the TV/IR sensor is allowed at any time

- Surveillance on the selected search radar video which can be displayed on the NA-25 associated MAGICS console: in this case the operator can directly designate a detected target to the tracking radar

- Interdirector Designation from/to another FCS

- Designation: processing of the designation orders originated by the Command and Control or EW System

- Optical call: processing of the designation orders originated by a Target Designation Sight

- Acquisition: can be performed in three different ways:

  - automatic detection and acquisition of targets crossing a preset guard ring
  - manual detection and automatic acquisition
  - manual detection and acquisition

. Automatic tracking of missile, aircraft and surface targets: it consists of a three coordinates filtering, through foe vector regeneration and trajectory prediction; manual override in angles and range is allowed at any time

. Air/Surface tracking and prediction models

. Gun orders computation: with parallax compensation, for up to two guns of different calibre; two ballistic alternatives are available for each gun, both of them loaded in the computer memory, with quick change-over capability

. Line-of-sight and line-of-fire stabilization

. Firing modes: anti-air (normal and barrage), surface, off-set

. Shore bombardment: direct, indirect modes

The NA-25, is fitted with autonomous automatic reaction capability, used as a back-up in case of failure to the Command and Control System: this capability is based on the threat evaluation and automatic selection of the priority target, performed through the processing of the air tracks originated by the video extractor connected to the ship's search radar.

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14. Abstract: This paper addresses the current capabilities at TNO-PML to assess the lethal performance of Surface-to-Air Missiles (SAM) against Anti-Surface-Ship Missiles (ASSM). The effectiveness of an interception of an Anti-Surface-Ship Missile by a Surface-to-Air Missile depends on the characteristics of the ordnance package of the terminal conditions of the interception. The ASSM threat can be represented by three generic target missiles, i.e. a Subsonic Sea Skimmer, a Supersonic Sea Skimmer and a Supersonic High Diver. The TNO-PML Lethality Assessment Computer Code calculates the single shot kill probability of a target for damage that is inflicted to the target by fragments, blast and direct hits.
The computer code includes a fuze model, a warhead model and a target vulnerability model and requires several sets of input data to specify the interceptions that are simulated.

ASSESSMENT OF THE LETHAL PERFORMANCE OF ANTI-ASSM MISSILES

(presented at the 30th DRG Seminar on the Defence of Small Ships against Missile Attacks, 12-14 September 1990, Ottawa)

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ABSTRACT

This paper addresses the current capabilities at TNO-PML to assess the lethal performance of Surface-to-Air Missiles (SAM) against Anti-Surface-Ship Missiles (ASSM). The effectiveness of an interception of an Anti-Surface-Ship Missile by a Surface-to-Air Missile depends on the characteristics of the ordnance package of the defending missile, the vulnerability of the target and the terminal conditions of the interception

The ASSM threat can be represented by three generic target missiles, i.e a Subsonic Sea Skimmer, a Supersonic Sea Skimmer and a Supersonic High Diver The vulnerability of the targets depends on the kill definition that is applied That is the target can be considered killed if it is not able to fulfil its mission (mission kill) or if its structure is instantaneously disrupted (structural kill).

The TNO-PML Lethality Assessment Computer Code calculates the single shot kill probability of a target for damage that is inflicted to the target by fragments, blast and direct hits. The computer code includes a fuze model, a warhead model and a target vulnerability model and requires several sets of input data to specify the interceptions that are simulated.

A special capability of the Lethality Assessment Computer Code is the ability to generate computer graphics that display the missile kill performance. For various warheads and fuze concepts the fragment, blast and direct hit kill probability can be plotted as a function of the intercept conditions and the time after detection. These graphics give the possibility to analyse the kill performance of a warhead against a target, to match fuze and warhead concepts and to establish appropriate warhead burst control algoritms.

1. INTRODUCTION

Hard kill weapons to defend surface ships from missile attacks mainly consist of Close-In Weapon Systems (CIWS), Surface-to-Air Missiles (SAM) and potentially directed energy weapons. Close-In Weapon Systems intercept Anti-Surface-Ship Missiles (ASSM) at shorter ranges from the ship while Surface-to-Air Missiles are able to engage attacking missiles at longer ranges.
To engage an Anti-Surface-Ship Missile, a Surface-to-Air Missile is launched from the defending ship and guided towards the attacking Anti-Surface-Ship Missile. In the following the defending Surface-to-Air Missile is called the missile and the attacking Anti-Surface-Ship Missile is called the target. During the terminal phase of the interception the proximity fuze of the missile detects the target and initiates the warhead. The explosive effects of the warhead may inflict fatal damage to the target, that causes a kill of the target.
This paper deals with the lethality assessment of Surface-to-Air Missiles against Anti-Surface-Ship Missiles. The effectiveness of a missile and target interception is expressed as the single shot kill probability (SSKP). This performance characteristic is used as an input parameter for studies that analyse the overall performance of ship defence systems utilizing Close-In Weapon Systems, Surface-to-Air Missiles or other systems.
Current and future Surface-to-Air Missiles are required to have high kill performances under difficult circumstances, i.e. low vulnerability of the target, large miss distances, high missile and target velocities and high crossing angles. To achieve these high performances it is important that the characteristics of the fuze and the warhead of the defending missile are properly matched in order to hit the target with fragments. The TNO-PML lethality assessment method pays special attention to the subject of warhead and fuze matching, as will be explained in the following.

2. ANTI-ASSM MISSILE LETHALITY ASSESSMENT

The lethality assessment of Surface-to-Air Missiles against Anti-Surface-Ship Missiles takes account of three damage mechanisms that may inflict damage to the target:

- blast
- fragments
- a direct hit

Blast is caused by the high explosive charge of the warhead and is only effective up to small miss distances. The lethal radius of a warhead can be enhanced by the addition of

fragments, that may damage a target up to large miss distances A direct hit occurs if the target collides with the missile before warhead initiation or with residual parts of the missile after warhead initiation

The kill performance of a Surface-to-Air Missile against an Anti-Surface-Ship Missile depends on a number of parameters:

- the characteristics of the ordnance system of the missile
  - warhead
    - total warhead mass (casing and high explosive)
    - number of fragments
    - fragment mass and velocity
    - fragment distribution
  - proximity fuze
    - single or double antenna beam
- the vulnerability of the target
  - (single and multiple) fragment
  - blast
- the conditions of the interception
  - missile and target velocities
  - crossing angle between missile and target velocities
  - miss distance and miss orientation
  - missile and target angle of attack
- the intercept range from the ship

For the lethality assessment calculations, the Anti-Surface-Ship Missile threat is represented by three generic target missiles:

- a Subsonic Sea Skimmer (SBS)
- a Supersonic Sea Skimmer (SSS)
- a Supersonic High Diver (SHD)

The vulnerability of these generic targets is reflected in three target vulnerability models that take account of the blast, fragment and direct hit damage mechanisms.

The vulnerability of an Anti-Surface-Ship Missile target does not only depend on the characteristics of the target but also on the kill definition of the target. With regard to this, a distinction is made between a mission kill, a structural kill and a recognizable kill of the target.

A mission or system kill occurs if the damage inflicted to the Anti-Surface-Ship Missile target is such that the missile falls outside the minimum range at which its warhead is

capable of causing significant damage to the target ship. A typical mission kill is caused by a small number of fragments that penetrate a vulnerable section of the target. Mission kills can be achieved out to large miss distances. Given a certain quantity of damage, the mission kill probability of the target depends on the target range-to-go, that is the distance from the ship at which the interception takes place. At longer ranges essentially all systems of the target are vulnerable, while at shorter ranges only the warhead of the target may be vulnerable.

A structural or catastrophic kill of the Anti-Surface-Ship Missile occurs if the damage inflicted to the target is such that the target breaks up instantaneously It is difficult to achieve a structural kill because it requires small miss distances. A structural kill is usually the result of damage caused by blast, by a high fragment density on a vulnerable section of the target or it is caused by a direct hit between the missile and target.

A recognizable kill of the Anti-Surface-Ship Missile occurs if the responses of the target after being damaged are such that the defending ship identifies the target as being killed. The identification whether or not a target is killed is called target kill assessment Kill assessment is used to re-engage targets by another Surface-to-Air Missile or by a Close-In Weapon System. The recognition of a target kill does not only depend on the quantity of damage that is inflicted to the target, but also on the capabilities of the defending ship, i.e. the resolution and accuracy of the sensors of the ship, the duration of the observation and the knowledge of the target. A structural kill or water impact of a target is often recognized as a kill, while slow target reactions that result in a mission kill may not by recognized as a kill.

A Surface-to-Air Missile usually has either a fragmentating or a continuous-rod warhead. The characteristics of the warhead have to be carefully chosen to achieve optimum kill performance. The fragment mass and shape can be controlled by using a warhead casing with preformed fragments or a casing with in or external grooves to control the break-up. The fragment velocity can be controlled by varying the ratio between the mass of the casing and the mass of the high explosive. The fragment distribution of the warhead can be controlled by the shape of the casing. A wide fragmentation beam can be achieved with a convex shape and a narrow beam by a concave shape of the casing.

The kill performance of a warhead can be optimized for a mission kill or for a structural kill of the target. A mission kill requires a wide fragmentation beam and small fragments whereas a structural kill requires large fragments and a narrow beam.

3. TNO-PML LETHALITY ASSESSMENT COMPUTER CODE

The computer code used by TNO-PML to assess the lethality of Surface-to-Air Missiles against Anti-Surface-Ship Missiles is a part of a more extensive Vulnerability and Lethality Assessment Code named TARVAC (TARget Vulnerability Assessment Code). This code is used to analyse the vulnerability of all kinds of targets such as vehicles, aircraft, helicopters and ships and the effectiveness of all kind of ammunition types such as armour piercing ammunition, shaped charges and fragmenting warheads. As is shown in Figure 1, the code which is used to assess the lethality of Surface-to-Air Missiles consists of four connected computer programs. For each program specified input data is required to simulate a particular engagement between a missile and a target.

The first part of the code is a computer program that simulates the operation of the proximity fuze. This program calculates the time at which the proximity fuze detects the target.

The detection of a target for a 60° crossing angle interception is shown in Figure 2. The target just touches the fuze cone that represents the leading edge of the sensitive area of the proximity fuze. The missile velocity Vm, the target velocity Vt and the relative velocity Vmt of the missile with respect to the target are indicated by vectors. The interception is drawn for a late miss of the surface-to-air missile, that is the missile passes behind the target.

Three sets of input data are necessary for the fuze program. First, the intercept conditions of the simulated engagements are required. The intercept conditions are described by the missile and target velocities, the crossing angle between the missile and target velocities, the angle of attack of the missile and the miss distance between the missile and target trajectories. Secondly, the fuze program needs a geometric description of the target. Finally, the proximity fuze has to be characterized by a number of parameters.

The fuze program also calculates the moment of warhead initiation and the warhead burst point with respect to the target. The moment of warhead initiation is found by adding the time delay to the moment of target detection. The time delay is calculated with the help of a warhead burst control algorithm, which may use several input parameters provided by the fuze and the terminal guidance algorithms.

The second part of the lethality assessment code simulates the fragmentation of the warhead. A large number of fragment trajectories is generated originating from the warhead burst point as provided by the fuze model. The trajectories are generated in correspondence with the warhead fragmentation pattern as indicated by the warhead

characterization data. This data comprises fragment velocities and masses, the total number of fragments and the spatial distribution of the fragments. To ease the operation of the warhead program all fragment trajectories are generated relative to the target. To calculate the relative fragment velocities the warhead model takes account of the missile and target velocities and the static fragment velocities.

The second part of the computer code also generates a number of trajectories that are used to determine the occurrence of a direct hit between the missile and the target. For this purpose a missile direct hit model is used that consists of a number of points representing the external geometry of the Surface-to-Air Missile. Just like the fragment trajectories a number of trajectories is generated that pass through the points representing the external missile geometry to simulate the translation of the missile.

The third part of the computer code determines whether or not the fragment trajectories and the trajectories simulating the missile translation intersect the target. For each target section this part of the computer code calculates the number of the hitting fragments and the striking obliquity of the fragments with respect to the surface of the target. For this purpose the target is represented by a three-dimensional model. This model is composed of several combinations of simple geometrical shapes that represent sections of the target.

Figure 3 shows a missile and target interception at the moment of warhead initiation which takes place at 0.5 ms time delay after detection. In this figure the impact positions of the fragments on the target are plotted by little dots.

Finally, the last part of the computer code calculates the single shot kill probability of the target for each simulated engagement. The single shot kill probability is computed by combining the total fragment kill probability, the blast kill probability and the direct hit kill probability. These probabilities are determined with the help of the vulnerability model of the target.

The total fragment kill probability of the target is calculated by combining the single fragment kill probabilities for all hitting fragments. The target vulnerability model ascribes these single fragment kill probabilities to each hitting fragment as a function of the fragment mass and velocity, the striking obliquity and the section of the target that has been hit.

The blast kill probability of the target is a function of the warhead mass and the distance from the warhead burst point to the target. A blast kill occurs if this distance is smaller than the critical blast radius as indicated by the target vulnerability model for each section of the target.

The occurrence of a direct hit kill is determined with the help of the trajectories that simulate the missile translation. If one of these trajectories intersects the target, the missile and target collide and the target is assumed to be killed.

4. SINGLE SHOT KILL PROBABILITY AS FUNCTION OF TIME AND MISS ORIENTATION

A special capability of the TNO-PML lethality assessment computer code is the ability to generate computer graphics that display the single shot kill probability of a missile and target interception as a function of time and miss orientation angle. These computer graphics can be used to analyse the kill performance of a warhead against a target for a certain miss distance or to match fuze and warhead concepts. Fuze warhead matching implies the tuning of the fuze and warhead characteristics to obtain good kill performance for all occuring intercept conditions

The computer graphics are made with the help of an imaginary cylinder that consists of the relative trajectories of the target for all miss orientations of the missile, as shown in Figure 4. This figure depicts a 60° crossing angle interception of a missile and two targets for different miss orientations of the missile. The early miss occurs if the missile passes in front of the target and a late miss occurs if the missile passes behind the target. For a certain miss distance magnitude the miss orientation can vary from 0° to 360°, that is from low to late, high, early and back to low again A low miss occurs if the missile passes below the target and a high miss if the missile passes over the target

In Figure 4 the targets are plotted at the moment of detection by the proximity fuze. The intersection points of the fragment trajectories with the relative target trajectory cylinder are plotted to indicate the direction of the relative fragment velocities all around the warhead.

The unfolded surface of the relative target trajectory cylinder with the intersection points of the fragment trajectories is shown in Figure 5. The targets for respectively a low, late, high and early miss of the missile are plotted for the moment of detection. The line marked by 'Detection" indicates the position of the target for all miss orientation angles of the missile at the moment of detection. The lines marked by "1 ms", "2 ms" and "3 ms" indicate the position of the target after 1, 2 and 3 ms time delay after detection. Finally, the line marked by "PCA" indicates the point of closest approach of the missile and the target.

The fragment impact points on the targets for a low, late, high and early miss of the missile are depicted in Figure 6 The figure is made for warhead initiation at 1 ms after detection.

For these 60° crossing angle interceptions the fragment velocity is perpendicular to the longitudinal axis of the target if the miss is late and parallel to the longitudinal target axis if the miss is early. This is why it is most difficult to hit the target in an early miss of the missile.

Finally, the single shot kill probability as a function of time and miss orientation angle is shown in Figure 7. This figure depicts the fragment, blast and direct hit kill probabilities by means of different colours on the surface consisting of the relative target trajectories. As is indicated, time is defined to be zero at the point of closest approach between missile and target. 0° and 360° miss orientation angles relate to a low miss of the missile, 90° to a late miss, 180° to a high miss and 270° to an early miss of the missile. Just as in the previous figure the curved lines indicate the positions of the target at the moment of detection and at 1, 2, 3 and 4 ms after detection.

This kind of computer graphics depicting the kill probability as a function of time and miss orientation can be made for various warheads, fuze concepts and intercept conditions. The pattern of fragment, blast and direct hit kill probabilities depends on the dimensions of the missile and the target, the warhead characteristics, the target vulnerability, the target range-to-go, the magnitude of the miss distance and the crossing angle between the missile and target trajectories. The lines that indicate the position of the target only depend on the characteristics of the proximity fuze.

This kind of computer graphics can be used for a number of purposes. First, the kill performances of various warhead concepts against a specific target can be compared. The characteristics of the warhead with optimum kill performance can be found by plotting a number of these graphics for different warhead concepts.

Secondly, the kill performance of a specific warhead against a target can be analysed for varying intercept conditions Figures 8, 9 and 10 show the kill performance of a warhead against a target for respectively 0°, 60° and 120° crossing angle interceptions. The kill performance of the warhead can be seen to decrease for increasing crossing angle of the interception.

Thirdly, the computer graphics can be used to match fuze and warhead concepts. As is shown in Figures 8 and 9, the warhead and fuze match properly for 0° and 60° crossing angle interceptions as good kill performance is achieved if the warhead is initiated immediately after detection of the target. For 120° crossing angle interception the warhead and fuze do not match properly as large time delays are required to achieve good kill performance.

Finally, the computer graphics can be used to establish warhead burst control algorithms. These algorithms compute time delays that are required to give the ordnance package of a Surface-to-Air missile good kill performence for all conditions of the

interception. To compute the time delays the warhead burst control algorithm may use several input parameters provided by the fuze and the terminal guidance.

5 CONCLUSIONS

To assess the kill performance of a Surface-to-Air Missile against an Anti-Surface-Ship Missile a lethality analysis has to be performed using the results of warhead and fuze studies. The result of the analysis can be reflected by a number of system lethality curves that display the single shot kill probability as a function of for example the miss distance, the crossing angle or the target range-to-go.

TNO-PML has the capability to perform such an integrated lethality analysis for fragmentating warheads against three generic Anti-Surface Ship Missile targets. The TNO-PML Lethality Assessment Computer Code calculates the single shot kill probability of missile and target interceptions for damage that is inflicted to the target by fragments, blast and direct hits. A special capability of the code is the ability to generate computer graphics that display the missile kill performance as a function of time and miss orientation. The computer graphics can be used to compare the kill performances of various warheads against a specific target, to analyse the kill performance of a specific warhead for different intercept conditions and to match fuze and warhead concepts.

LETHALITY ASSESSMENT COMPUTER CODE

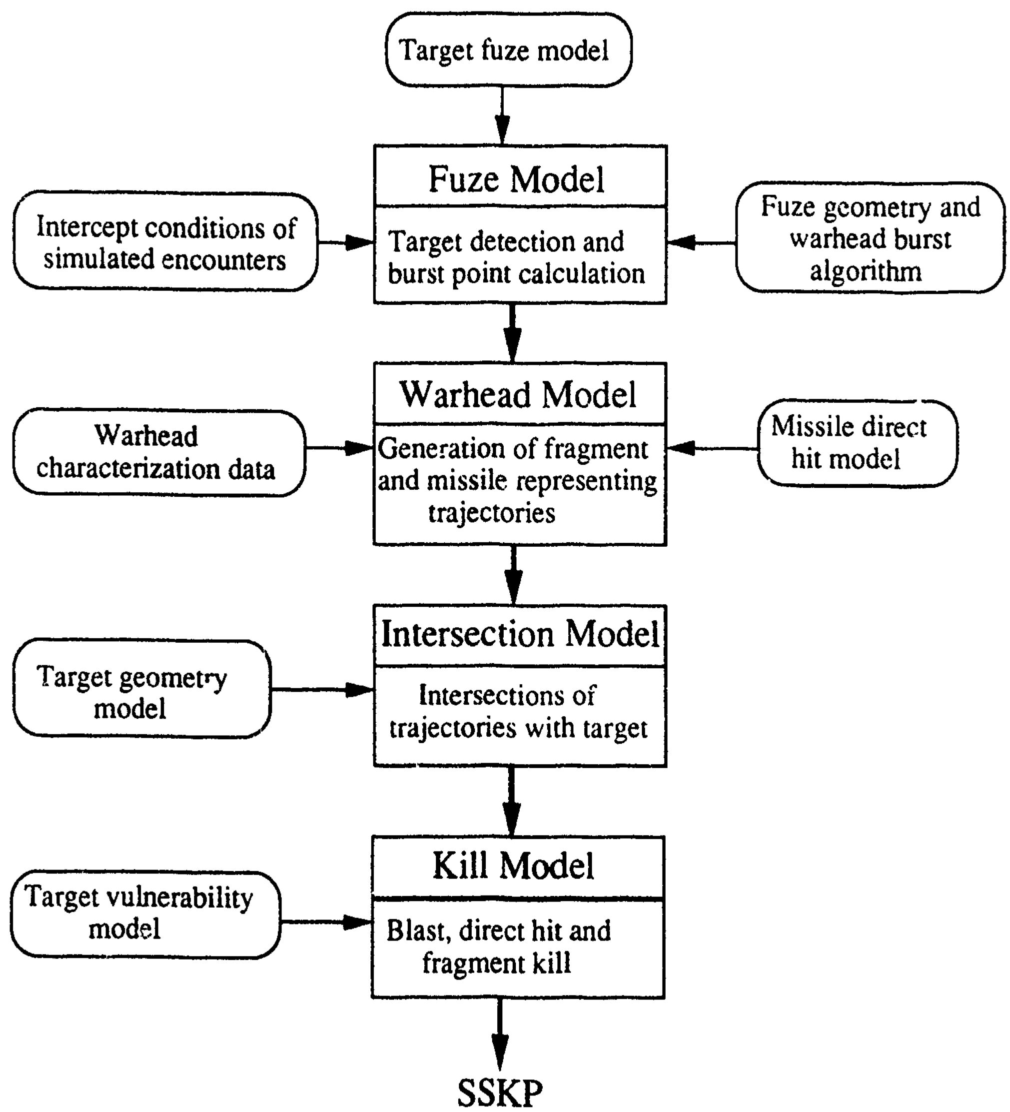

Figure 1: Lethality Assessment Computer Code

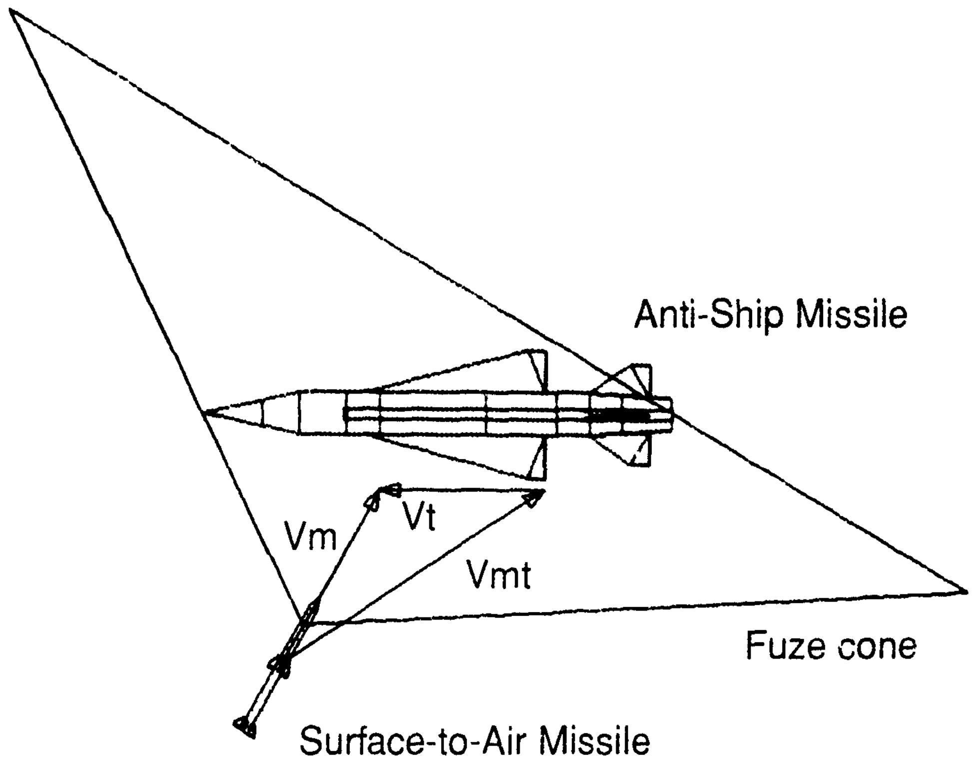

Figure 2: Detection of the ASM by the proximity fuze of the SAM (Late miss of the SAM)

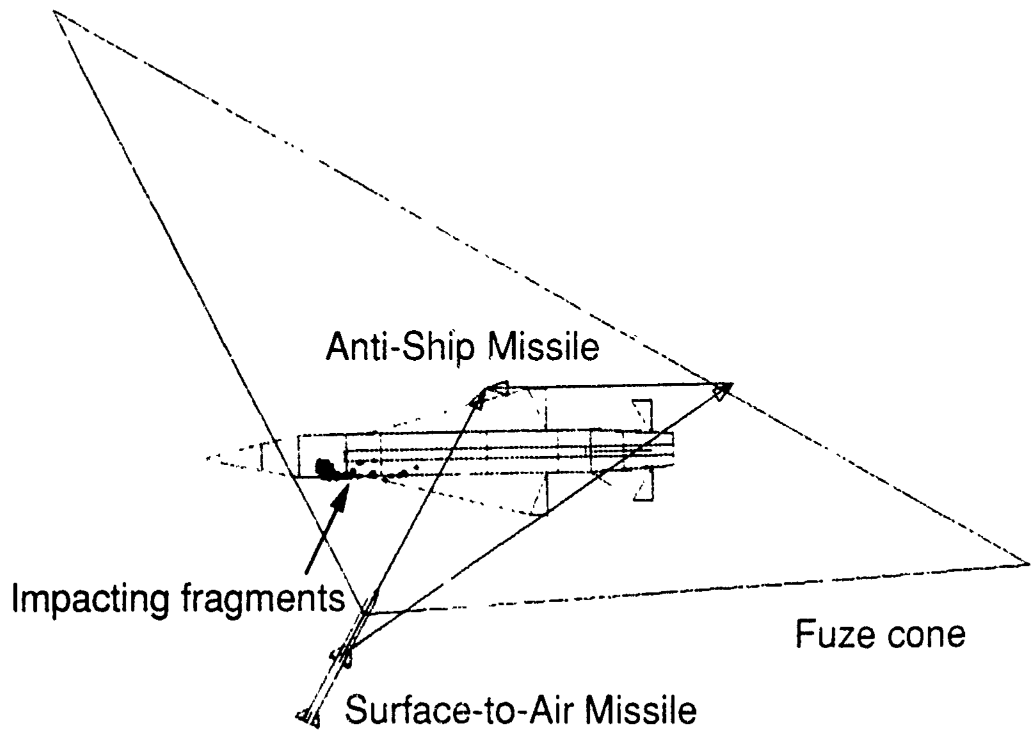

Figure 3: Impacting fragments on the ASM

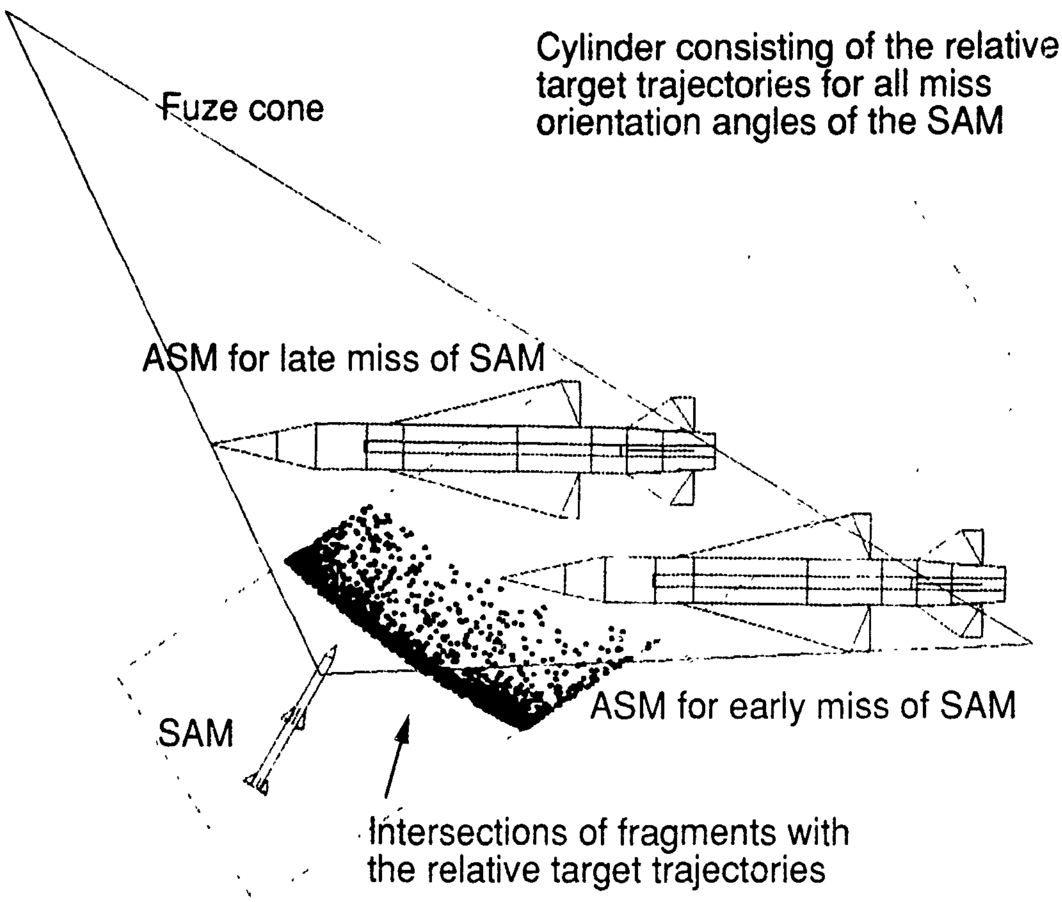

Figure 4: ASM for early and ASM for late miss of the SAM and the intersection points of the fragment trajectories with the relative ASM trajectories for all miss orientation angles

Targets at the moment of detection projected on the opened out surface of the cylinder that consists of the relative target trajectories

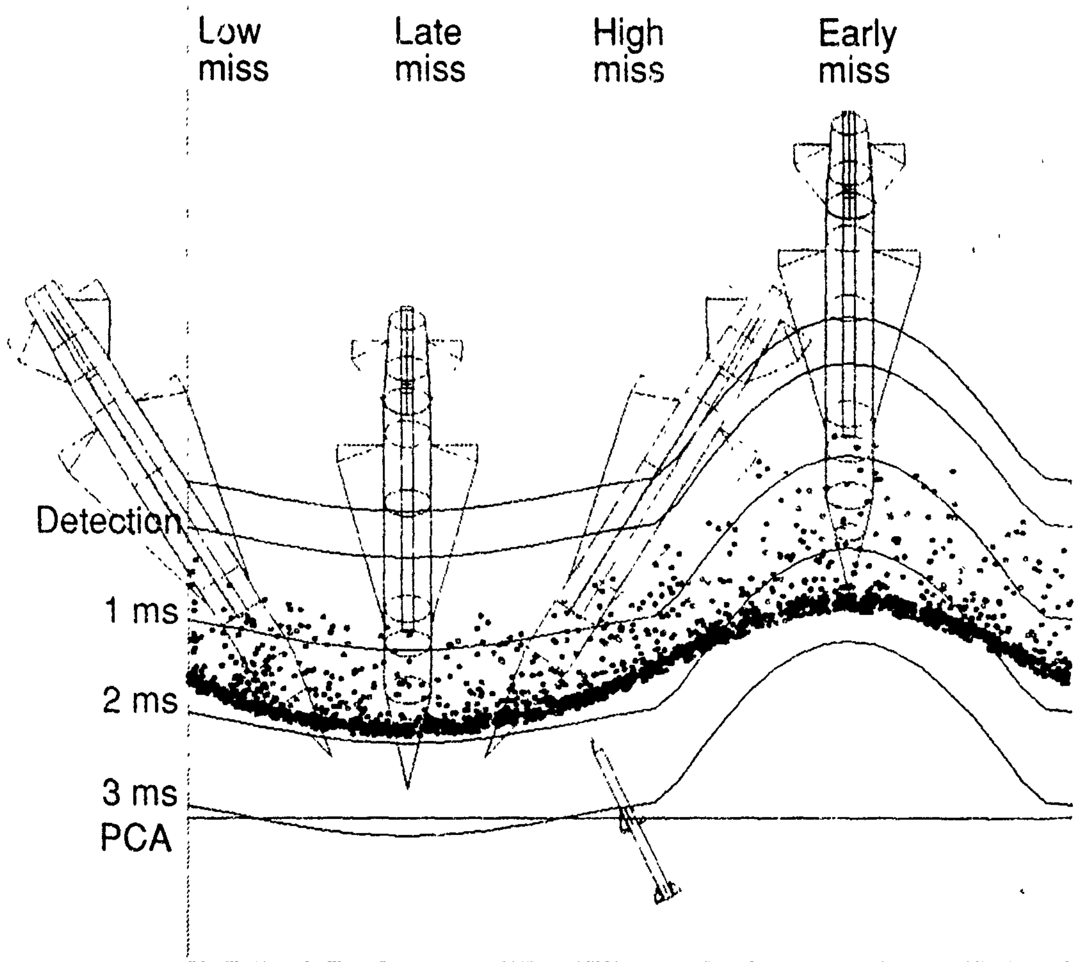

Figure 5: Lines indicating the target position after a certain time delay and the intersection points of the fragment trajectories with the relative target trajectories for all miss orientation angles

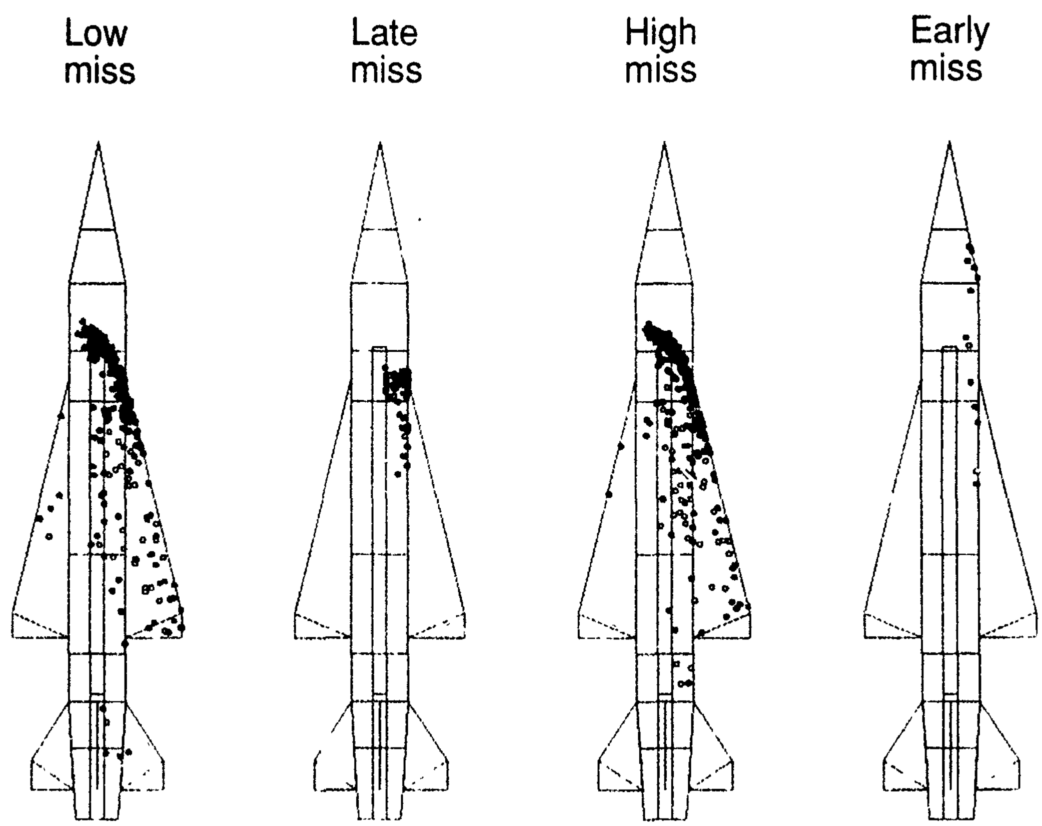

Figure 6: Impacting fragments on the ASM targets for warhead initiation at 1 ms time delay after detection

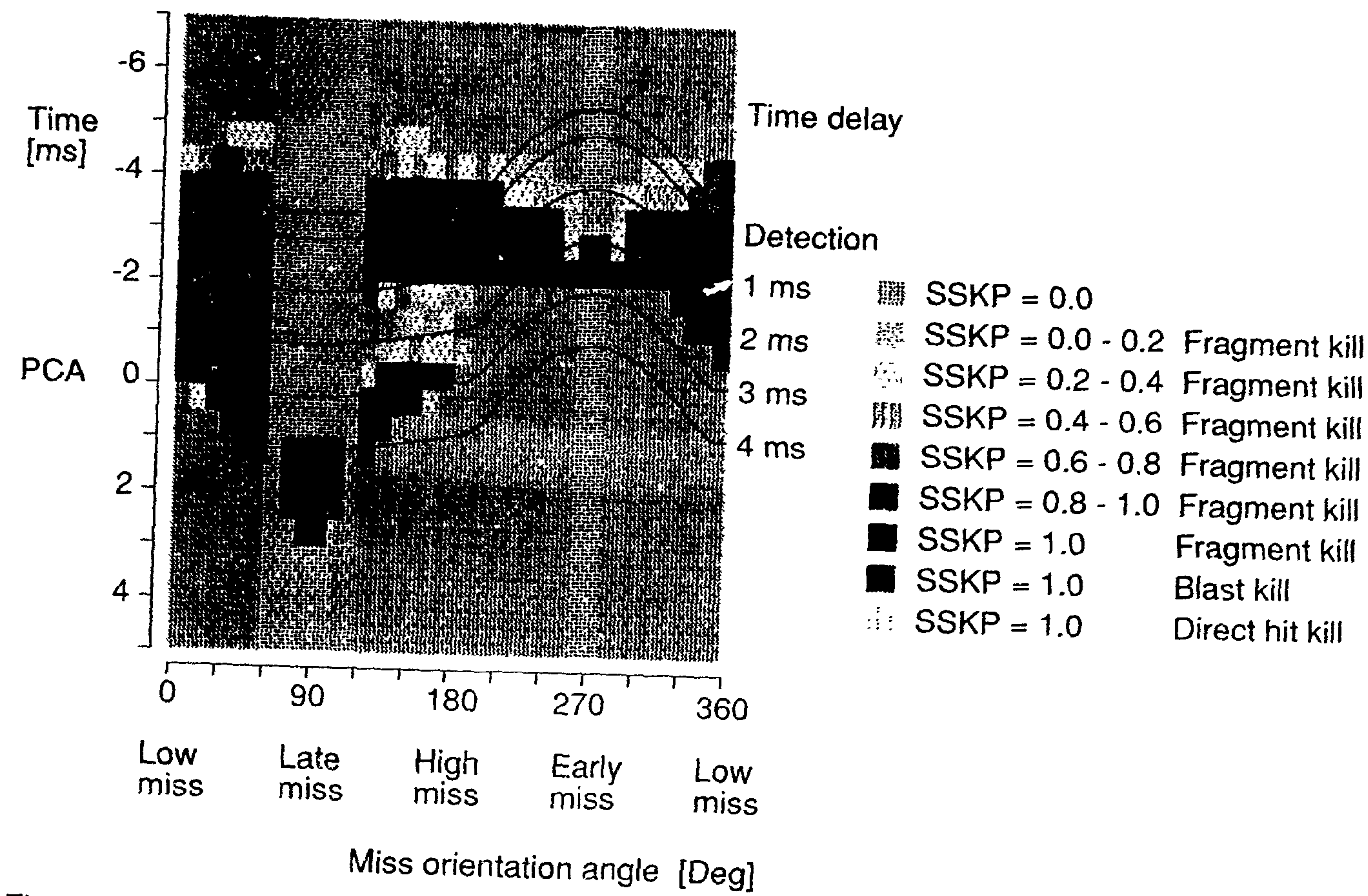

Figure 7: SSKP as function of time and miss orientation angle

30.16

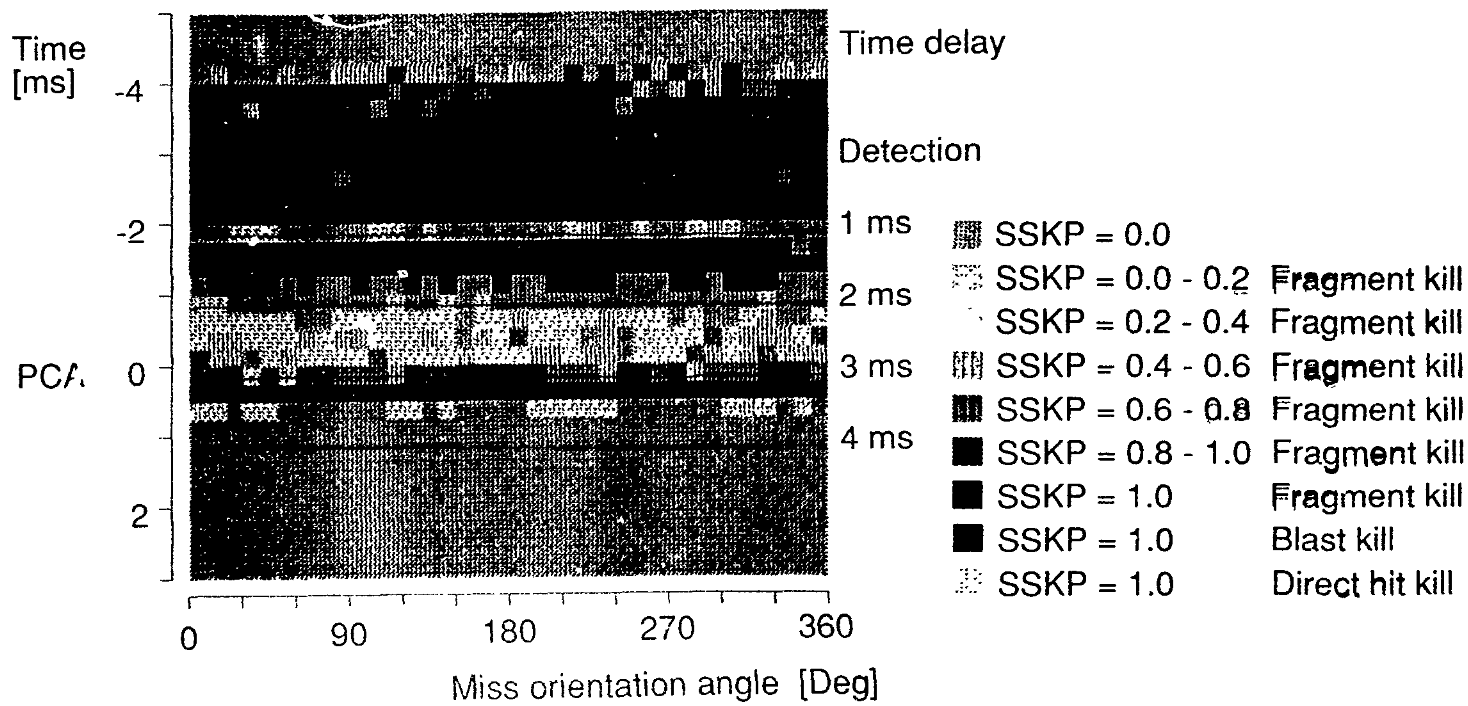

Figure 8: SSKP as function of time and miss orientation angle for 0° crossing angle

30.17

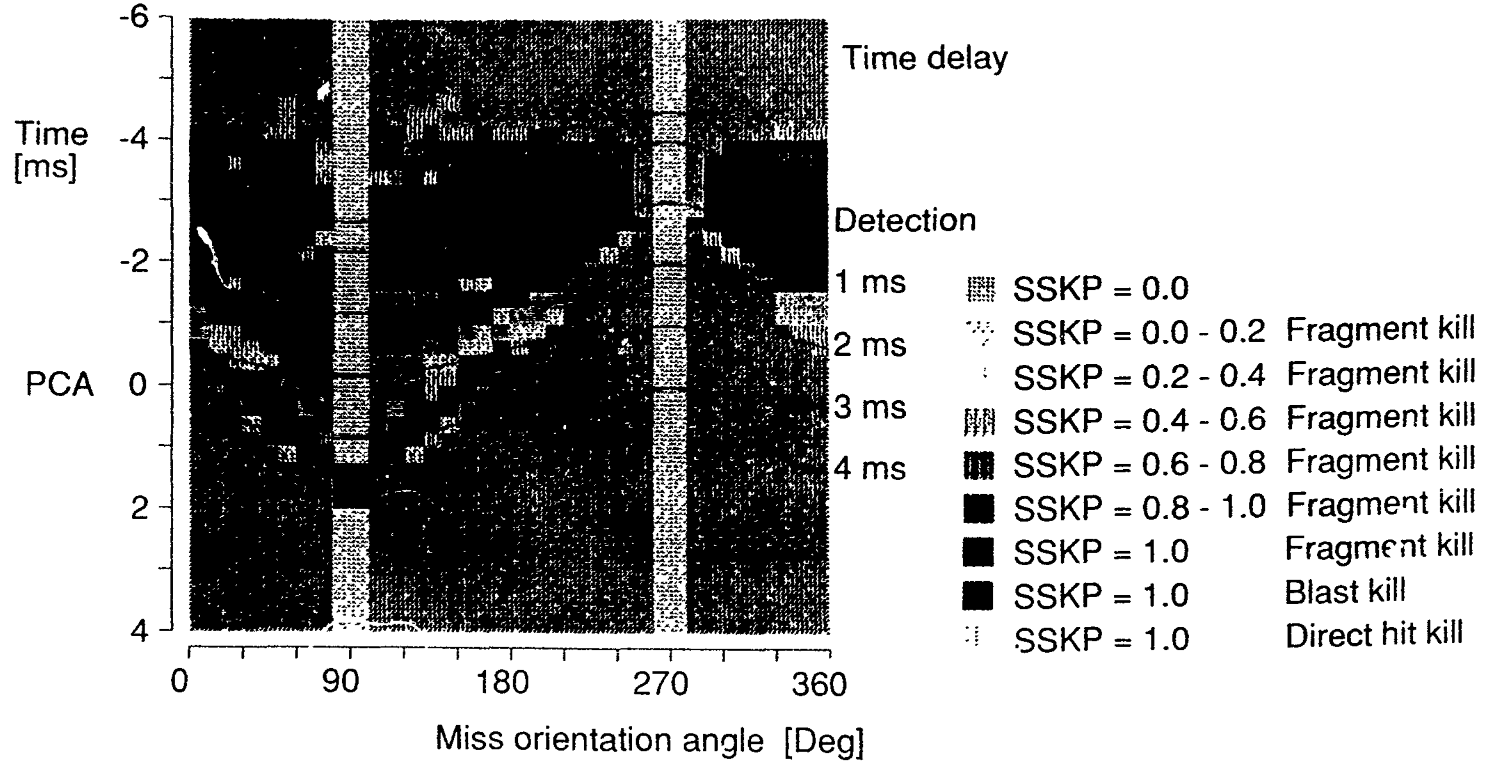

Figure 9: SSKP as function of time and miss orientation angle for 60° crossing angle

30.18

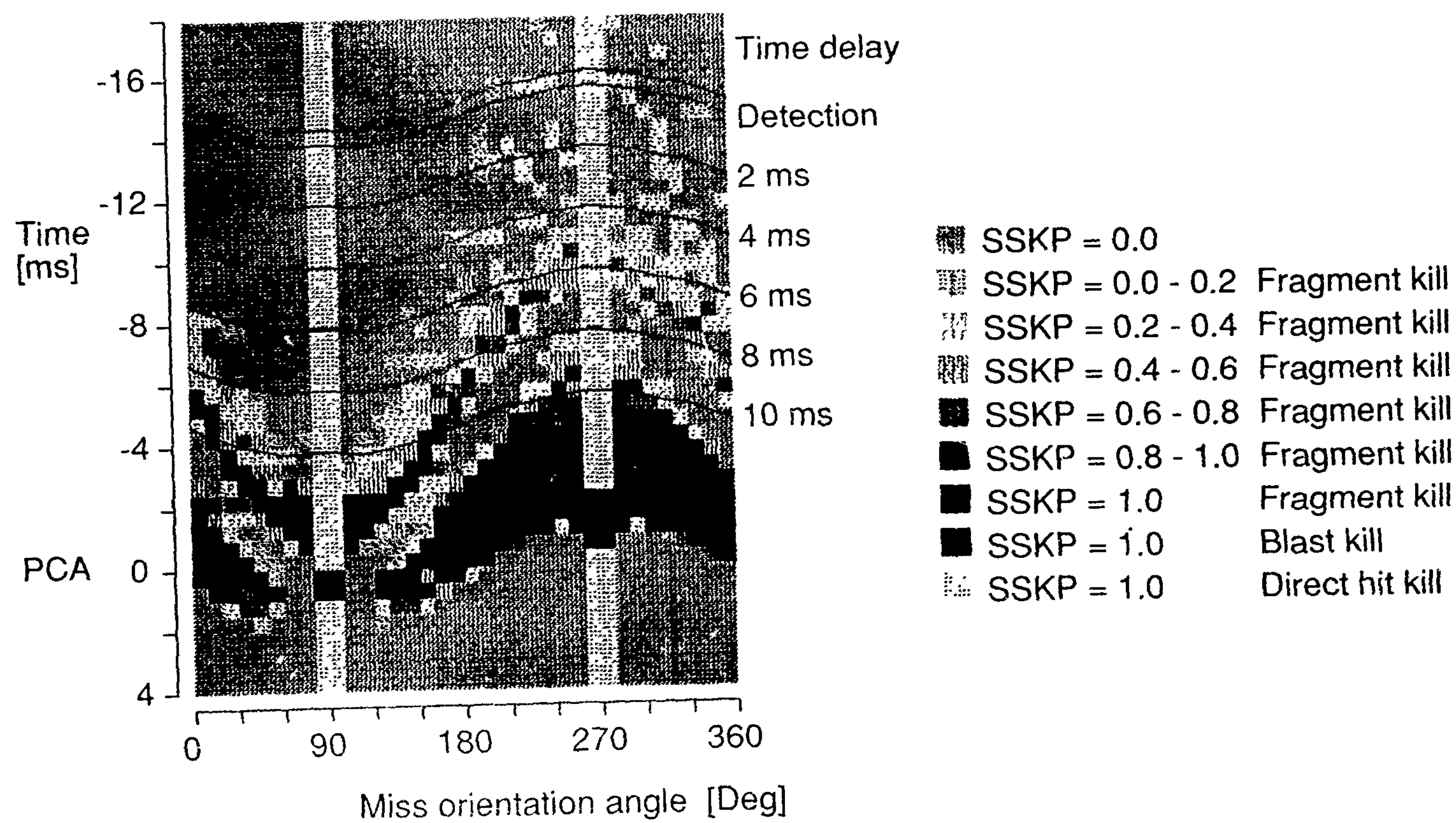

Figure 10: SSKP as function of time and miss orientation angle for 120° crossing angle

30.19

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14. Abstract:

It was about 18 years ago, that people in the terminal ballistics section of the then Technological Laboratory TNO started to consider the behaviour of a target being hit by a specific projectile, and how the residual value of such a target could be quantified. Following research institutes abroad an approach was chosen in which use was made (and still is) of so-called vulnerability models. In these models firing at the target is simulated by the computer.

One of the associated problems is the validation of the model, as well as the reliability of the results. Some of the results are presented as a series of firing trials carried out in the last 3 years on two small frigates of the "Roofdier" class, which were taken out of commission by the Royal Netherlands Navy. The main objectives of those trials were the validation of codes and testing specific aspects related to vulnerability problems.

VULNERABILITY ANALYSIS OF SURFACE SHIPS IN THE NETHERLANDS AND ITS EXPERIMENTAL VALIDATION

(presented at the 30th DRG Seminar on the Defence of Small Ships against Missile Attacks, 12-14 September 1990, Ottawa)

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ABSTRACT

For years technological research for defence purposes was mainly aimed at the ammunition itself. Most attention was paid to things like manufacture, storage capability combined with keeping qualities and the terminal ballistic effects of the ammunition.
It was about 18 years ago, that people in the terminal ballistics section of the then Technological Laboratory TNO started to consider the behaviour of a target being hit by a specific projectile, and how the residual value of such a target could be quantified
Following research institutes abroad an approach was chosen in which use was made (and still is) of so-called vulnerability models. In these models firing at the target is simulated by the computer.
One of the associated problems is the validation of the model, as well as the reliability of the results. The proposed paper describes the recent research on the assessment of the vulnerability of surface warships to fragments and blast performed at the Prins Maurits Laboratory (PML/TNO), which is one of the institutes of the Netherlands Defence Research Organization TNO. This work was started in 1980.
Further, some of the results are presented of a series of firing trials carried out in the last 3 years on two small frigates of the "Roofdier" class, which were taken out of commission by the Royal Netherlands Navy. The main objectives of those trials were the validation of codes and testing specific aspects related to vulnerability problems.

* senior scientist, air systems branch

** chief terminal ballistics branch of the Research Group Ballistics & Rocket Technology

1. INTRODUCTION

In addition to the understanding of the weapon effects from a ballistic point of view, it is necessary to assess the vulnerability of targets subjected to these effects. This research should provide a better understanding of the correct employment of weapons in addition to a better defence of targets to those effects. From recent experiences, e.g. during the Falklands crisis, it became clear that surface ships are quite vulnerable to the effects of a hit from an anti-ship missile. Apart from the fragmentation effects, the violent forces from the internal blast may cause considerable damage and loss of life. In addition to the "standard" vulnerability method addressing the effects of fragments and/or projectiles, a structural failure model due to the blast from internal explosions was also required. To assess the complete or overall vulnerability, the results of both models should be combined. To address this problem in more detail, a certain scenario is assumed, where a surface ship is attacked by an anti-ship missile, see Figure 1 This scenario yields two possibilities.

1. the missile warhead explodes outside, albeit close to the ship
2. the missile hits the ship, and detonates in a compartment

In order to defend the ship from this missile, air defence weapons should be employed to counter the missile threat, by premature detonation of the warhead due to (multiple) projectile impact (e.g. Goalkeeper system) or by destroying critical components of the missile guidance and control system leading to a pre-emptive destruction It should be borne in mind that destroying the guidance system or other flight-critical systems will not be sufficient to avoid a hit when the missile is too close. In the Weapon Effectiveness Group at PML/TNO models have been developed to compute the flight trajectory of missiles with damaged controls or degraded stability . With these models the possible point of impact of the crippled missile can be computed.

When a missile hit cannot be avoided, the ship must be capable of surviving the internal explosion of the warhead.

2. VULNERABILITY MODEL

In order to assess this weapon-target interaction more precisely, vulnerability models were developed. In the past, most efforts in this field were performed by the United States, followed later on by European countries. In the vulnerability models, the target of interest is modelled using a solid model technique. With such solids the complete target can be designed to a certain accuracy with respect to geometrical layout. Each

component present in the target consists of solids, such as boxes, spheres, cones, parallelepipeds etc., or by combinations of such solids. Furthermore, the weapon effect is simulated by shotlines intersecting this target model according to specified penetration criteria assigned to the solids. Once the intersections are known, the computer can retain all critical components being penetrated, and the damage to the components is assessed according to specified damage or kill criteria When all damaged components are known, and their degraded states, the final kill probability of the target is assessed for this particular weapon-target interaction Following US institutes dealing with vulnerability matters in the past, PML/TNO also developed their vulnerability code, culminating in the Target Vulnerability Assessment code (TARVAC), see Figure 2 This code is intended to assess the vulnerability of targets subjected to the effects of projectiles and fragments.

However, when dealing with missile warhead explosions in ships, the main damaging effect was understood to be the blast from the internal detonation. The violent forces emanating from this explosion are sufficient to rupture bulkheads, walls etc., jeopardizing the structural integrity of the whole ship. Due to the ship's structural layout, a different approach to the "usual" vulnerability method was required Instead of a solid modelling technique, the ship's structure is divided into structural elements, such as walls, decks, hull plating etc. Given certain specifications of the structures, e.g plate thickness, stringer pitch, allowable yield stresses etc., the non-linear dynamic response of all loaded elements are computed, given the location of the detonation centre The blast and the quasi-static pressure are calculated for the different structural elements in the explosion compartment Specified failure criteria are included to compute the maximum response of a certain structural element, before failure occurs.

Should a wall fail, the pressure is allowed to expand into the adjacent compartment, where additional walls can be loaded. This whole process of dynamic panel/wall response in conjunction to a loading assumption from internal blast, culminated in the DAMINEX code, the acronym for DAMage from INternal EXplosions, see Figure 3.

The main intention of DAMINEX is the intermediate solution between complex Finite Element/Finite Difference methods on the one hand and simplified methods on the other where the physical parameters are evenly distributed before calculation.

However, neither code had the opportunity of being tested and results were mainly checked with foreign experimental results.

3. "ROOFDIER"-CLASS TRIALS

Fortunately, a few years ago the Royal Netherlands Navy offered the possibility to set up experiments with two decommissioned frigates of the "Roofdier" class ("Roofdier"=beast of prey), named the "Fret" and the "Wolf" respectively. Despite their small size they nevertheless offered the possibility to check both codes in detail, using explosive charges TNT, scaled warheads, live warheads etc.. In addition, PML/TNO was able to perform measurements on board during the shots, e.g. pressure/blast, accelerations (shock), strains and thermal effects (temperature) and to check their measuring techniques.

The main objectives for those trials were:

- Testing the TARVAC code
- Investigating Ballistic Protection measures
- Testing the DAMINEX code
- Testing the Critical Blast Distance definition
- Investigating the capabilities of naval shells
- Investigating the blast resistance of watertight ship doors
- Investigating the internal blast induced by external explosions

The trials were conducted over a period of three years and were extensively instrumented and recorded. The results of all those trials are still in the process of evaluation and will subsequently be reported.

4. TARGET VULNERABILITY ASSESSMENT (TARVAC)

The main issue for testing the TARVAC code was to investigate the fragment distribution and perforations from High-Explosive shells against actual components. The shells used varied from 76 mm up to 203 mm (8 in) artillery shells. The particular set-up of this test is depicted in Figure 4, where an artillery shell detonation is simulated located near the steering room of the "Wolf" frigate. Figure 5 shows the actual experimental results, which should be compared with the computational results of Figure 4. In the simulations, the code allows the presentation of the actual penetration hole size, depending upon the shape number and mass of each individual fragment. With these tests an update of the correct shape number and its random selection for natural shaped fragments could be derived. In addition, the measures with respect to ballistic protection could also be investigated, see Figure 6. These measures depend on the necessity to apply additional armour and the material used. To this end, special

warheads were designed, in particular to create high velocity fragments with a predetermined mass and fragment distribution. During the "Roofdier" trials several industrial materials were applied and the results were subsequently reported or are still in progress.

5. DAMAGE FROM INTERNAL EXPLOSIONS (DAMINEX)

The testing of the DAMINEX code was one of the major objectives of the trials Numerous charges from 0.5 kg up to 15 kg TNT were detonated in several compartments to check computational results, to test structural adaptations and measuring equipment. Figure 7 depicts a (DAMINEX) computer model of the "Roofdier" class frigate, showing the decks and walls of this vessel. The code has been applied to compute the effects of an internal detonation of a High-Explosive charge TNT equivalent to a missile warhead detonation. Fragment effects, however, are not included This simulation was tested with actual firings of TNT charges, e.g. as depicted in Figures 8 and 9, where 8 kg TNT was detonated in the aft sleeping room (Volume = 77 m^3) Note the venting plume jetting through a hole in the hull, which was deliberately cut so as to simulate the entrance hole of the missile The damage from this explosion is depicted in Figures 10 and 11 showing the exterior and interior damage respectively. It must be noted that the structure in this case was loaded to its maximum capability.

Apart from unexpected events during actual live firings, the results from the tests corresponded with the computational results quite well.

A dramatic picture is shown in Figure 12 where a charge of 15 kg TNT was detonated in a compartment, so as to simulate the effects of a real missile warhead detonation inside the Command and Information Centre (CIC) of a frigate. Pressure-time records, both from the explosion compartment and the adjacent compartment are depicted in Figure 13, where the effect of venting is clearly visible As might be expected, the damage was severe, as may be seen in Figure 14, where the upper deck was torn off completely.

One of the results was that the code generally offers a good prediction capability, but falls somewhat short in predicting the pressure in adjacent compartments if the interfacing wall fails. This effect is presently being studied in more detail.

6. THE CRITICAL BLAST DISTANCE (CBD)

The critical blast distance (CBD) is the distance at which the structure starts to crack due to the external blast load. The blast load simply consists of the reflected pressure upon a panel, which can be derived from classical blast wave theories. Usually, normal reflection is assumed and the panel is assumed to be loaded instantaneously. Based on dynamic response calculations of a panel using two-dimensional single-degree-of-freedom approximations for the panel response, the critical distance can be derived where failure of the panel would occur. Figures 15 and 16 show a 50 kg charge detonated in front of the superstructure. The damage from this external explosion can be seen from Figure 17, showing the deflection of the wall. From theoretical considerations, the CBD curves were derived for the hull and superstructure respectively, which compares very well with the measured deflections, see Figure 18. It should be noted that these curves are valid for all loading realms For distances closer than the CBD, ballistic protection is not useful, because blast damage will prevail On the other hand, for distances greater than the CBD, ballistic protection may be useful, because fragment damage will prevail there.

7. CAPABILITIES OF NAVAL SHELLS

An interesting aspect performed during the "Roofdier" class trials was the investigation of the damage potential of general naval calibre shells The shells considered were the 76 mm and 120 mm shells, as used by the RNLN Figure 19 depicts the layout of the 76 mm shell, and the damage capability is illustrated in Figure 20. In general, the damage inflicted by this calibre yields perforations extending over one bulkhead, while blast effects were negligible.

The largest calibre, the 120 mm shell, see Figure 21, gave a better performance, see Figure 22. Here, the perforations extended over three bulkheads, while the blast was quite considerable.

8. BLAST RESISTANCE OF SHIP DOORS

One of the additional flaws encountered during the 120 mm trials was the unexpected behaviour of the doors, as found in this frigate. During the blast tests, four doors situated over a distance of 20 m were blown out from their mountings. Figure 23 shows a door frame bulged due to the blast from a 120 mm shell. This event marked a

series of trials to investigate the behaviour of the standard door used in the RNLN frigates due to the internal blast. Figure 24 shows a standard door, indicated GW-door (GW - Guided Weapon). Figure 25 and 26 show the damage after the explosion of 1.5 kg TNT in the cable locker to the frame and door respectively.

Based upon these results scientists at PML/TNO designed a blast-resistant door, based on membrane action. This door, designated the PML-door (Figure 27), was tested during the trials. A close-up of the clamp mechanism is shown in Figure 28.

From the results obtained during the "Roofdier" trials it may be concluded that the membrane action is very efficient in carrying severe blast loads but that clamping forces are also very severe It should be noted that the door tested was an adapted version of the standard door, due to budgetary reasons. A completely new design would behave even better. Despite its lower mass, the PML-door successfully sustained the ultimate loads of the conventional door Reports of the tests are still in progress and the results will have a positive impact upon the design of newer developments.

9. CONCLUSIONS

From all activities performed or still going on in the analysis of the vulnerability of surface ships threatened by anti-ship missiles, it may be concluded that the existing codes could be updated by the data obtained. The fragmentation effects are better understood and could be simulated with better accuracy The internal blast from warhead detonations inside compartments is also better understood with respect to phenomenology The damage to the "Roofdier" class frigates enabled an improvement in wall panel response methodology and blast loading concept These subjects are still under development At present, directional effects of internal blast from a failing wall are being studied in more detail. The external blast effects could be comprised into the critical blast distance concept (CBD) and may be useful in further analyses

Finally, it may be concluded that the "Roofdier" trials proved to be very successful, both from the managerial and scientific point of view. The vast amount of data are still being processed and evaluated. The roar of the "Roofdier" will echo for many years.

LIST OF FIGURES

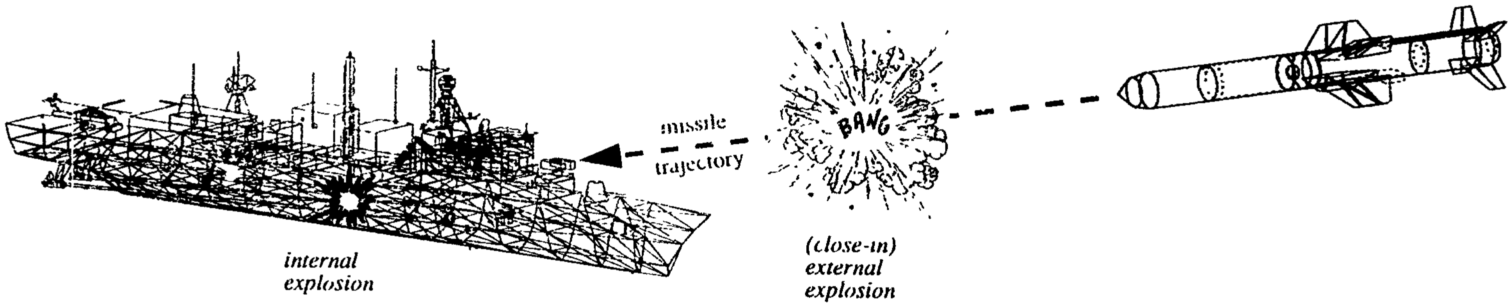

Figure 1. Missile attack upon a surface ship

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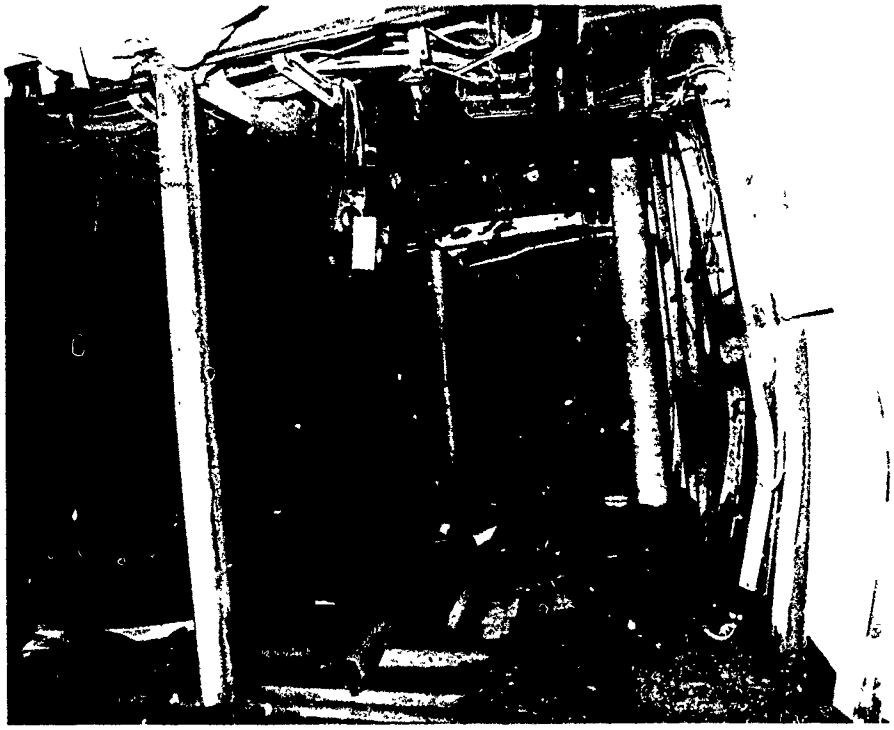

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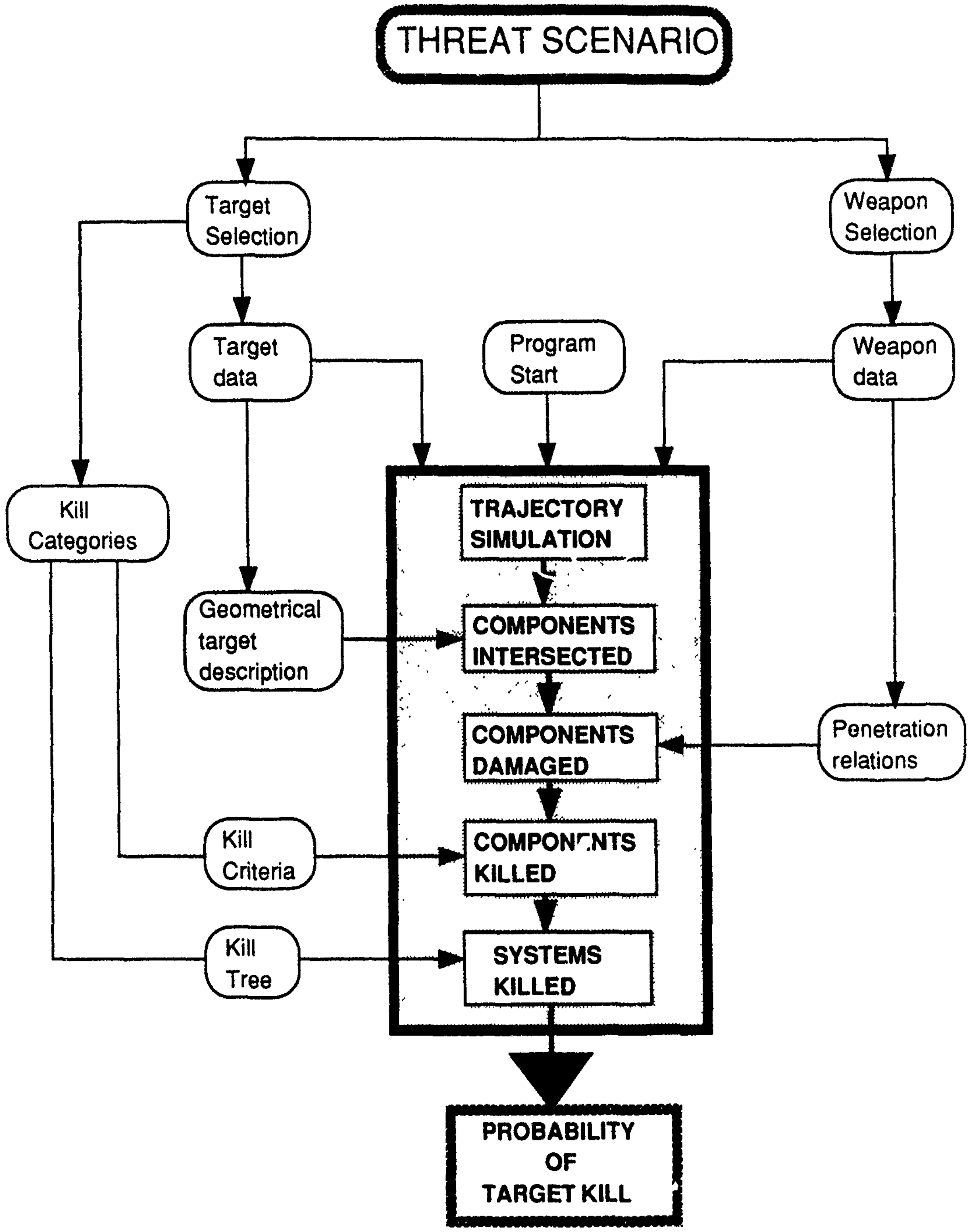

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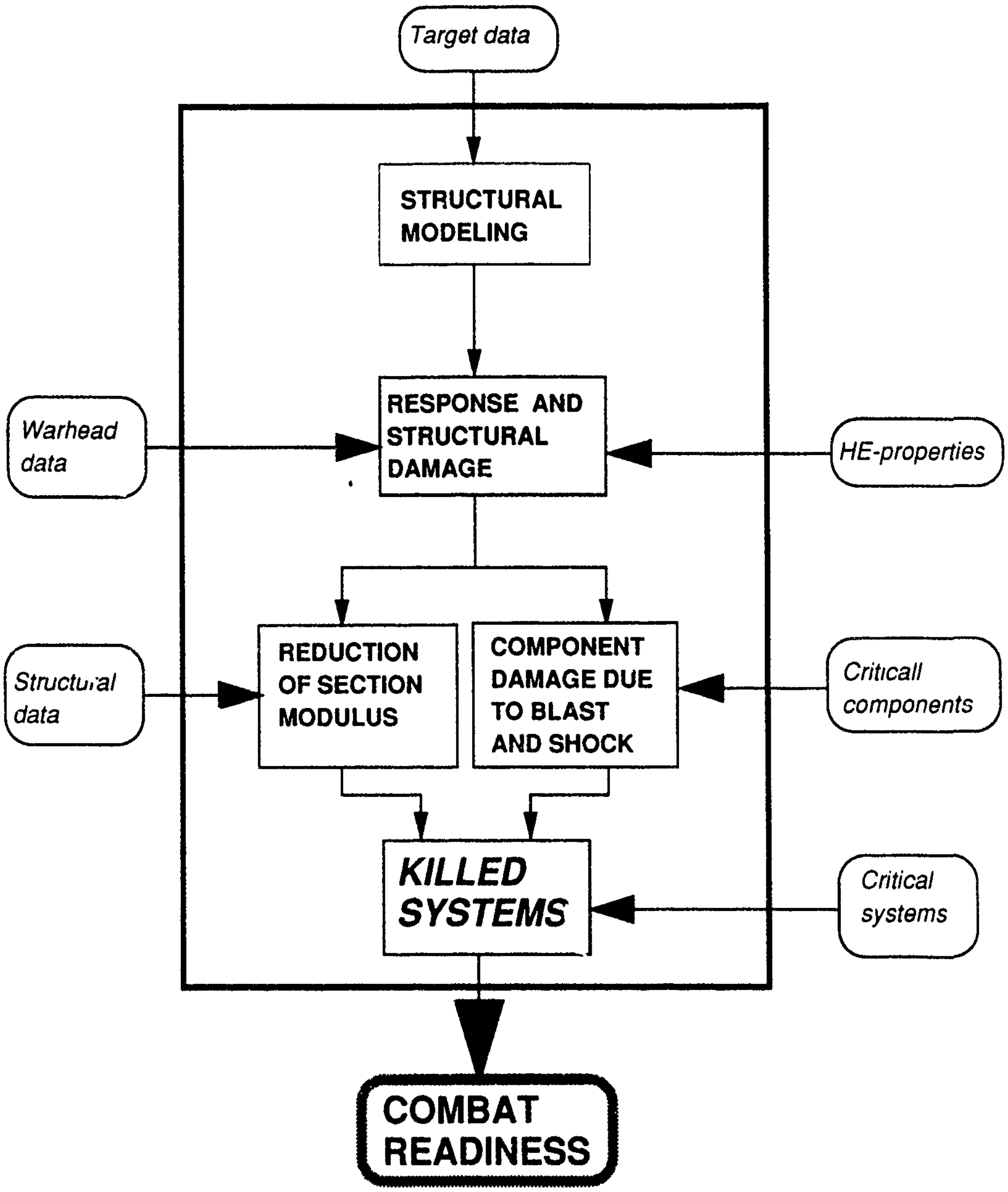

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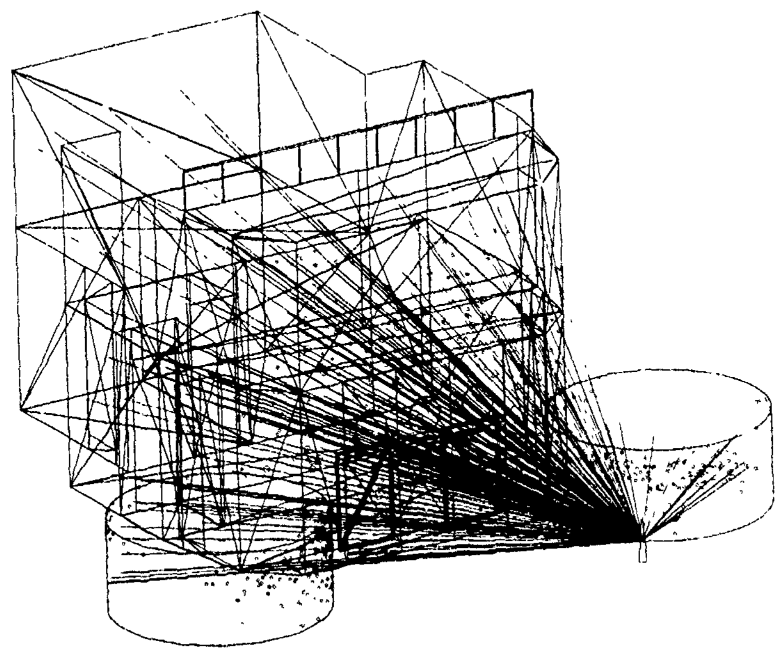

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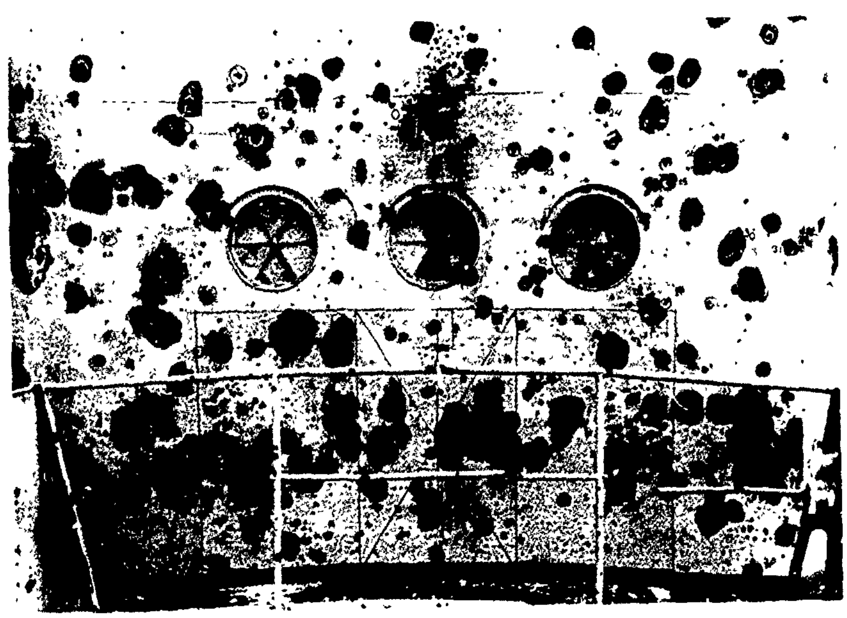

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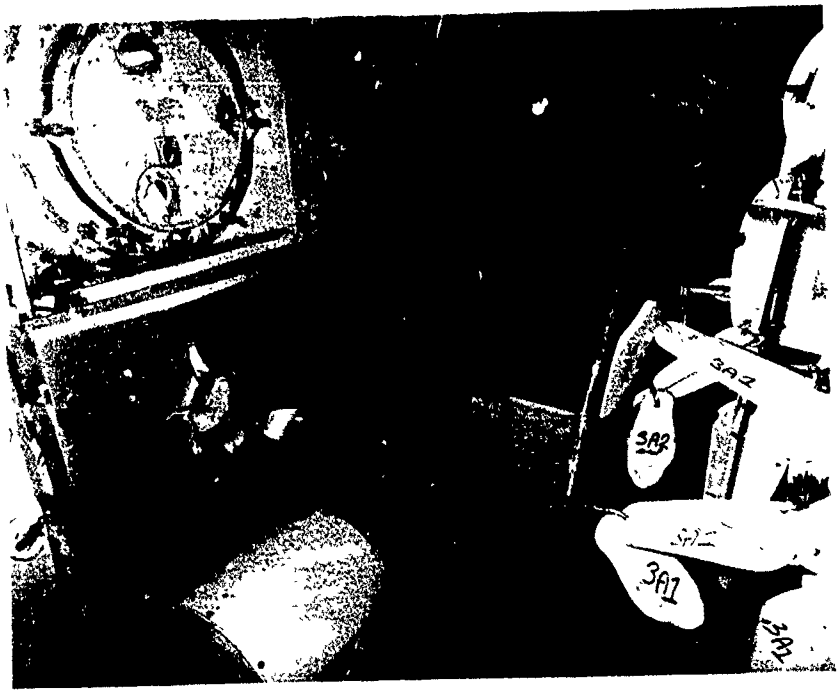

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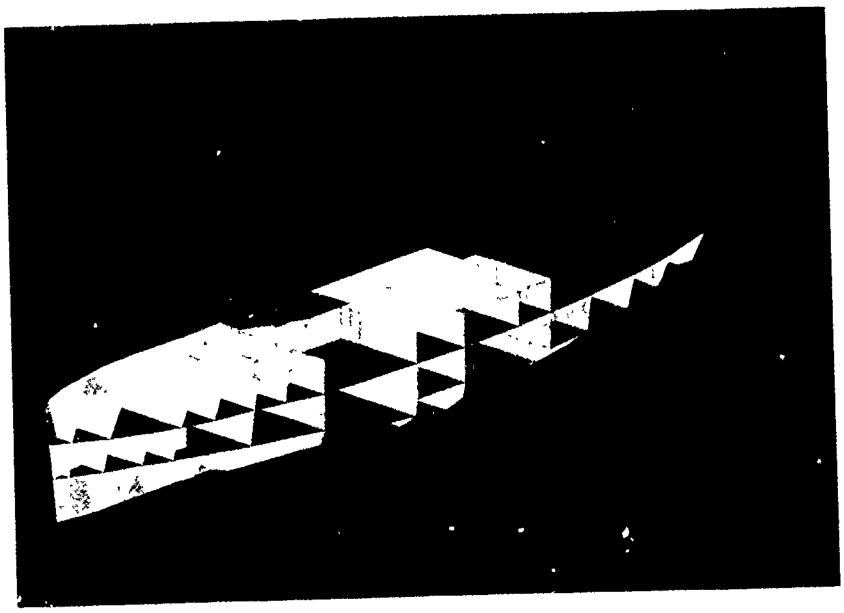

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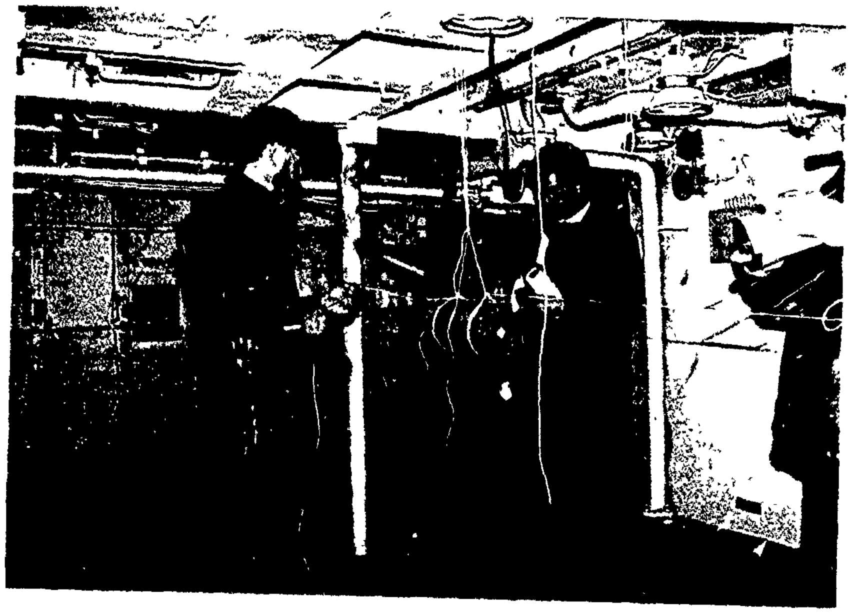

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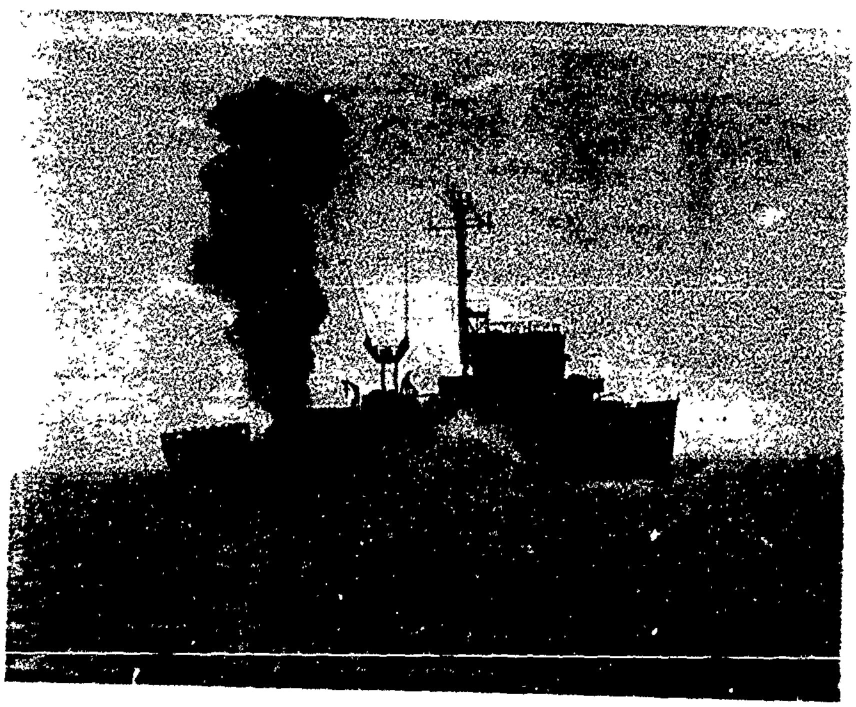

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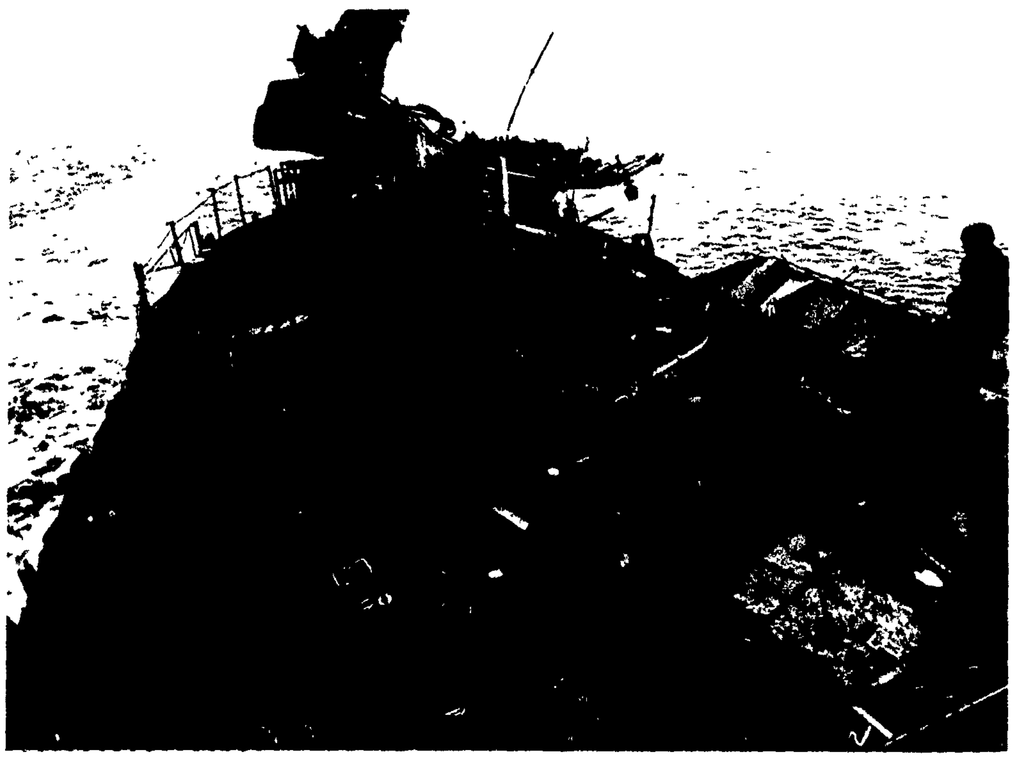

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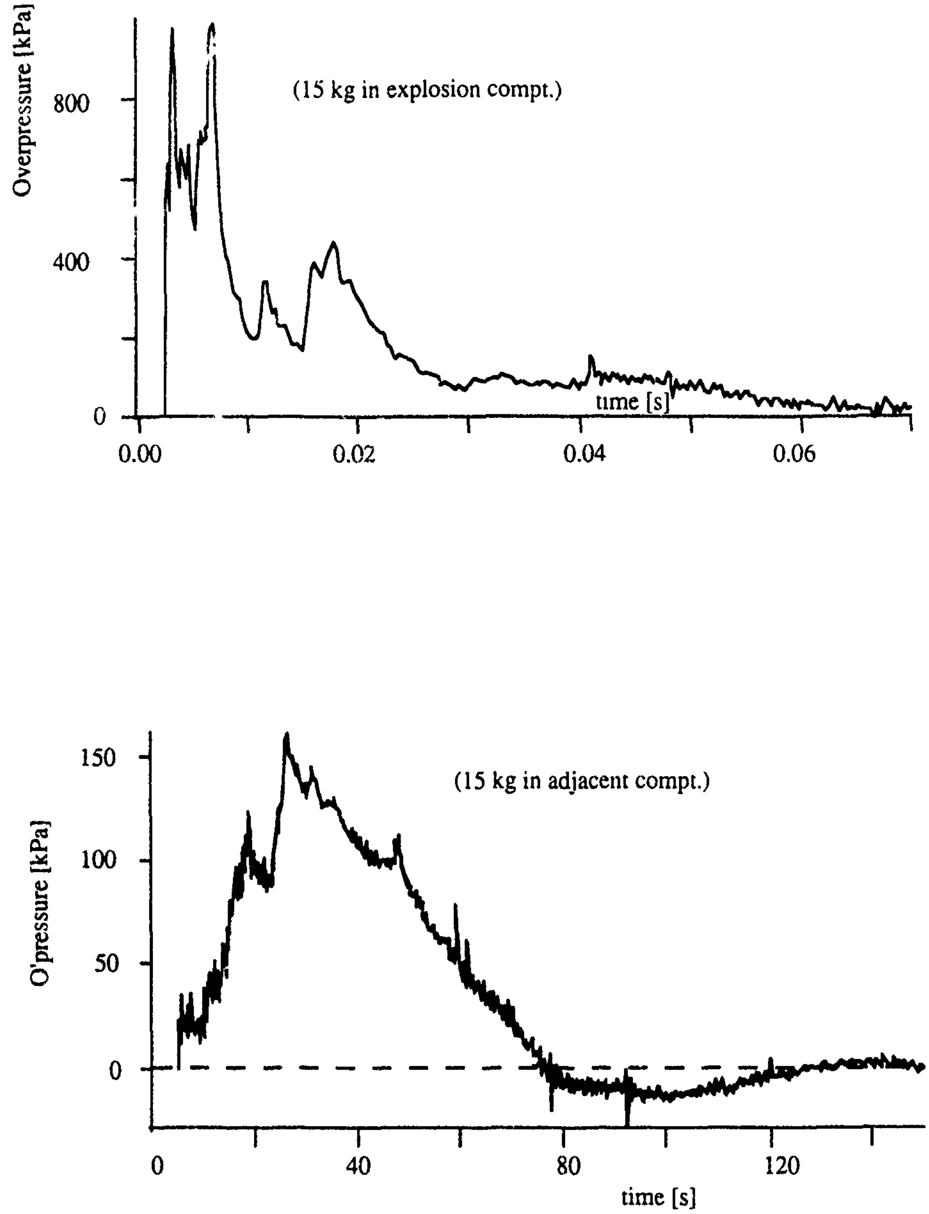

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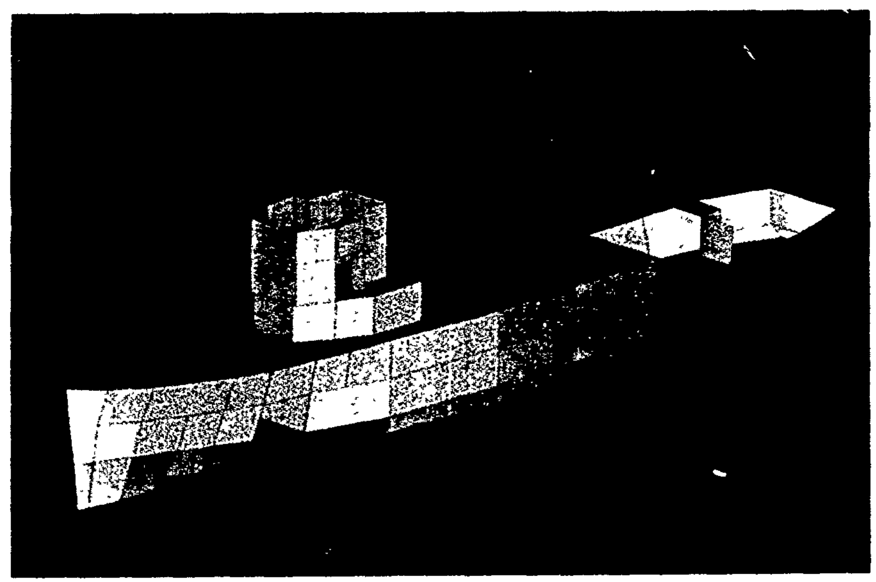

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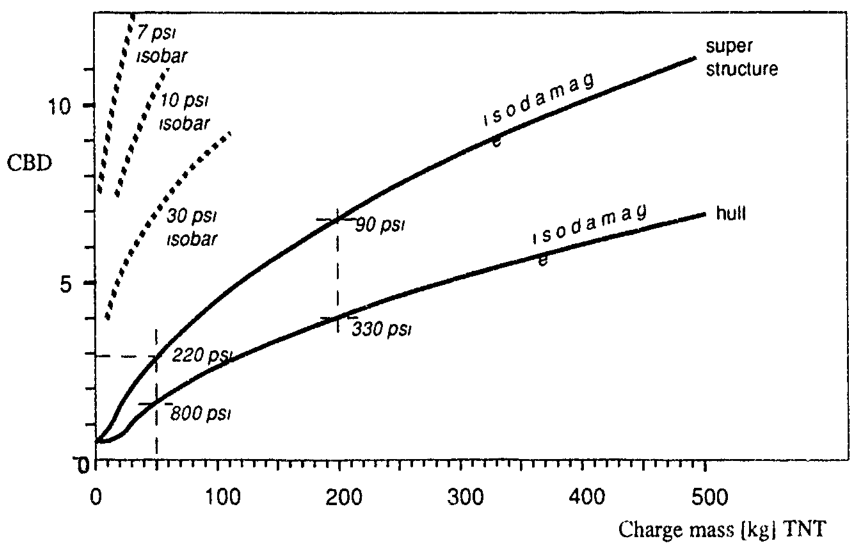

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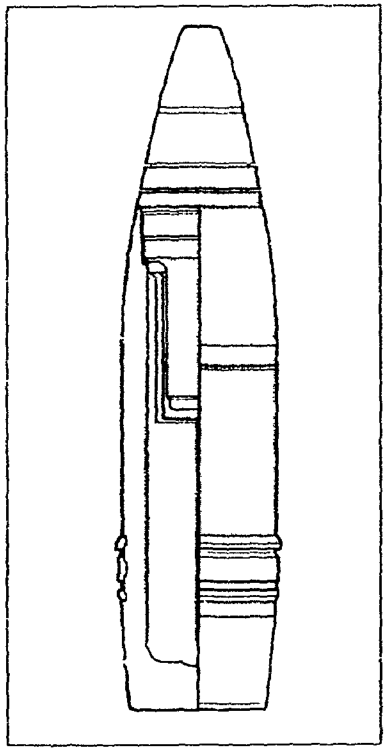

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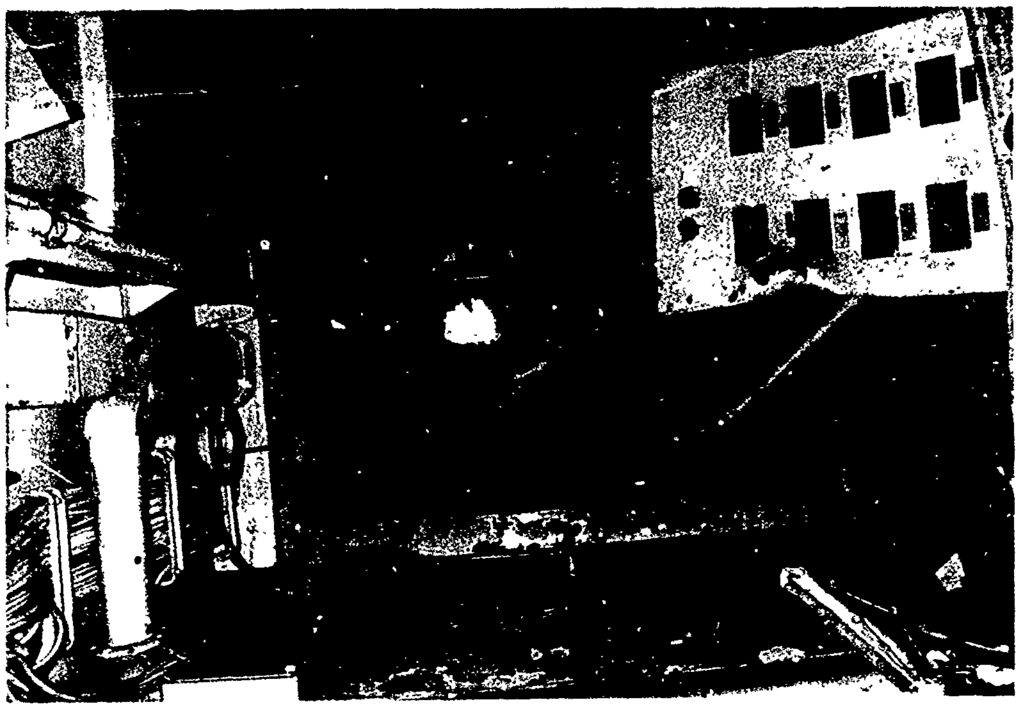

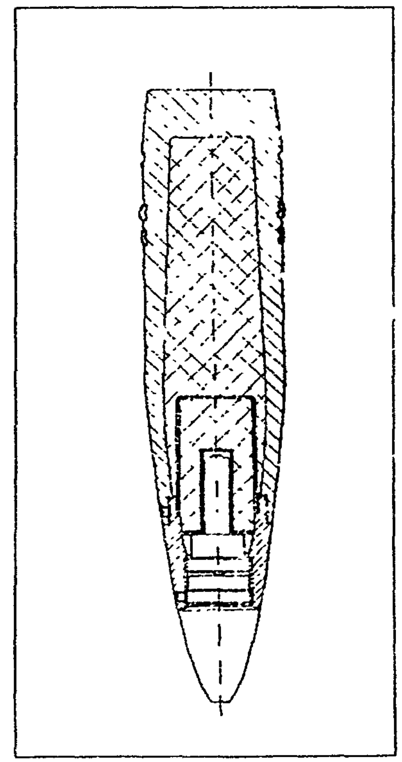

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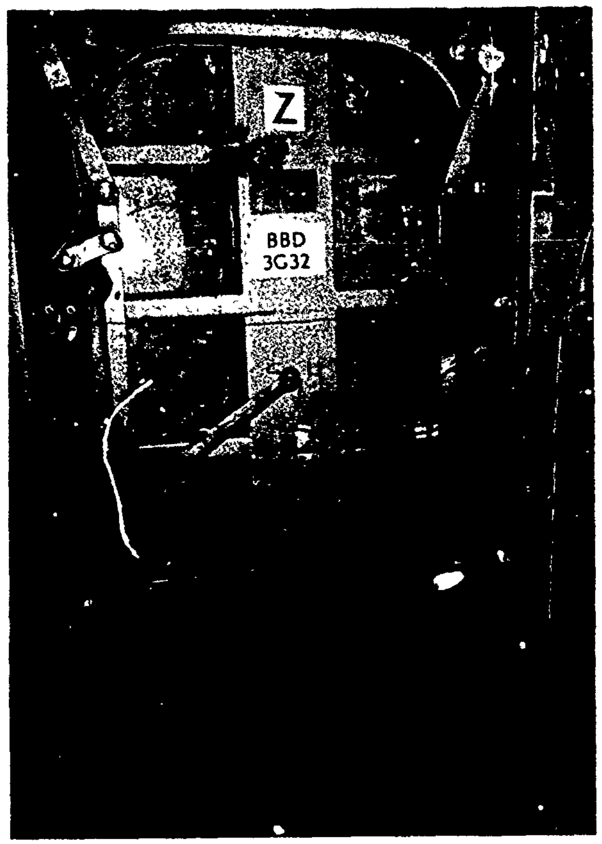

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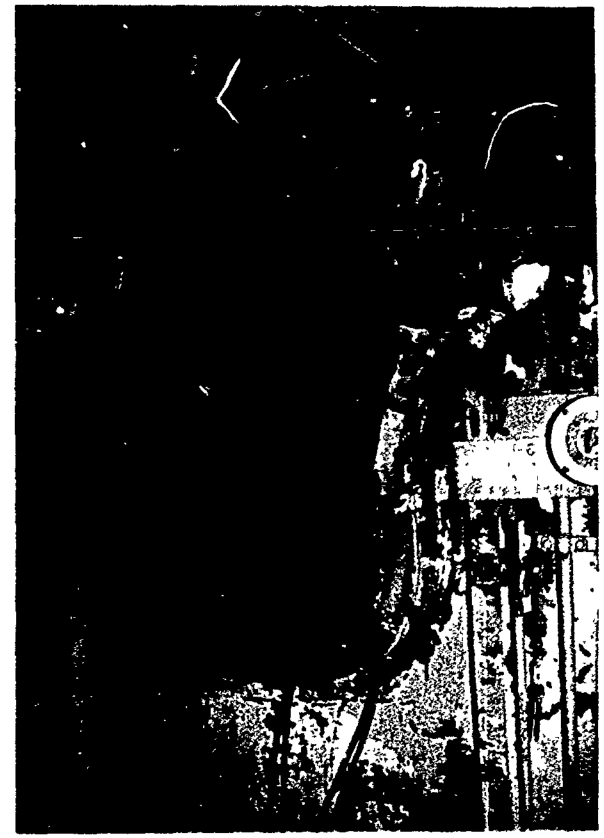

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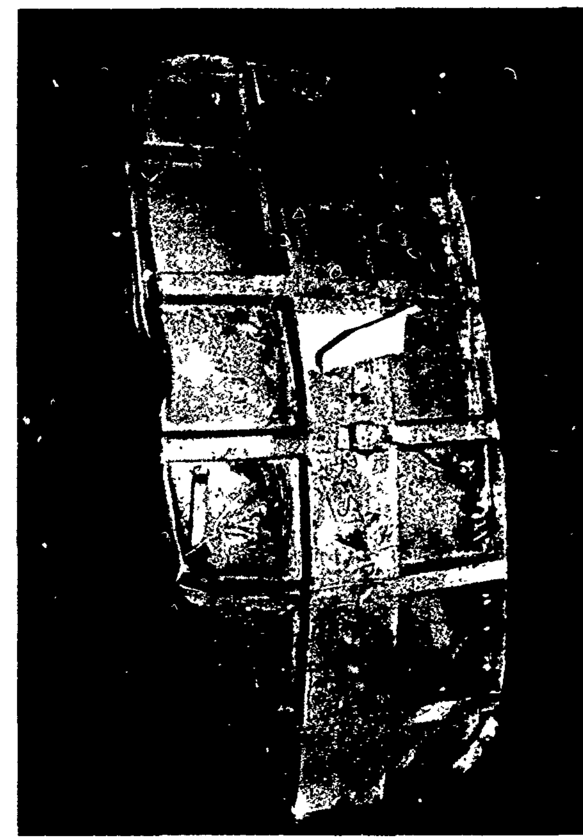

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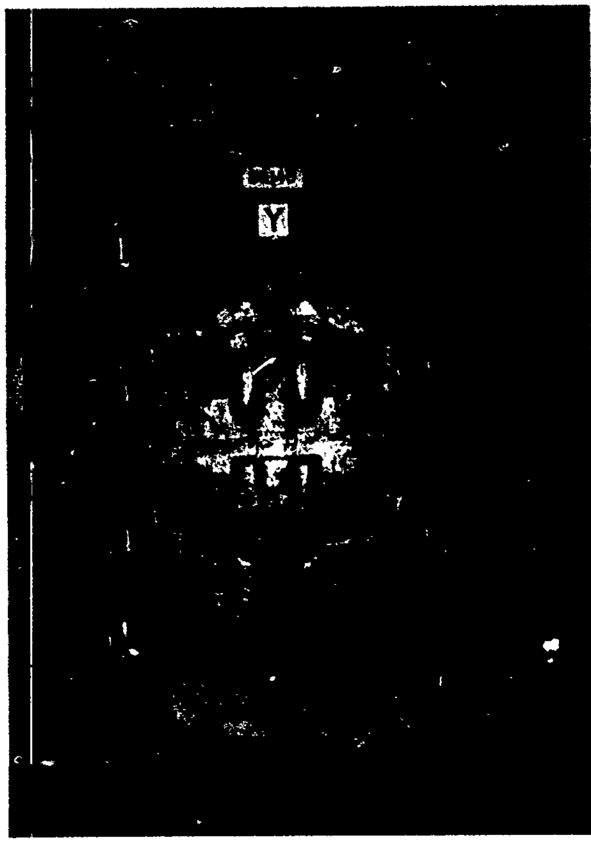

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14. Abstract:

It is commonly assumed that the trajectory of an attacking missile in homing phase is straight.

Missile trajectory is in reality influenced by the target tracking errors, due to target glint, that in combination with guidance law and missile transfer function, produce a comples trajectory.

Complex missile trajectories produce degradation of gun based defence systems which use direct impact ammunitions.

In case of intentional disturbance on missile seeker created on board ship, coordination with fire control is necessary and possibilities are indicated.

SEA SKIMMING MISSILE ATTACK NATURAL MANOEUVRES

PRESENTATION
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SEA SKIMMING MISSILE ATTACK NATURAL MANOEUVRES

AUTHORS:

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CONTENT

1. INTRODUCTION.

A Sea skimming Missile is a higly dangerous threat because of its small size, high speed and damaging capability.

With the exception of intentional evasive manoeuvres, the missile guidance system drives the missile towards the target trying to go through the shortest path.

It is commonly assumed that the trajectory of an attacking missile, during the homing phase, is straigth, but the presence of tracking errors induces variations on the missile trajectory also in absence of intentional manoeuvres.

The principal contribution to the tracking errors is the "Glint" phenomenon.
It is well known that the apparent radar center of a target moves during the flight due to the target motion.
This movement, in combination with the proportional guidance law and the missile transfer function, causes variations around the theoretical trajectory.
Since the "Glint" amplitude depends on the apparent target angular dimension with respect to the missile, in the case of a ship target, the effect of the glint noise is appreciable.

In this paper simplified models of the missile homing and of the radar glint noise are utilized to reproduce the glint and its effect. The validity of the results of the models used is confirmed by experimental data.
The missile model considered is a typical sea-skimming missile of the fourth generation, characterized by inertial and active radar homing guidance, with a cruising speed of 0.9 Mach and height of flight of 2-3 m above the sea level in the terminal attack phase.

The targets considered are small and medium size military ships as Frigates, Corvettes and Fast Attach Craft.

The principal and indesidered effect of these manoeuvres is the performance degradation of a direct impact gun based defence system like CIWS.
The extent of this degradation is calculated by a complex simulation of gun defence system and of the missile motion.

Intentional disturbance on missile seeker, created on board ship, ECM - CHAFFS, can increase the missile manoeuvres and then influence the CIWS performance.

The coordination in the use of active and passive defence system are useful to optimize the ship survivability.

2. DESCRIPTION OF GLINT PHENOMENA AND MISSILE MODEL.

2.1. MISSILE GUIDANCE MODEL.

The missile guidance model has been realized considering the mathematical representation of:

- Autopilot and aerodynamic transfer function.
- Homing guidance law.
- Seeker transfer function.
- Glint Noise.

2.1.1. Autopilot and Aerodynamic Function.

The missile is modelled as an object flying above the sea at the speed of 0.9 Mach.

The autopilot drives the missile by a lateral acceleration setting the rudders. The representation the complete autopilot, including stabilization loops and the aerodynamics response, is a first order transfer function:

$$F(s) = \frac{1}{Ts + 1}$$

where T is the time constant of autopilot.

The maximum lateral acceleration of the missile is fixed to 10 g.

The height of the missile, controlled by the autopilot is, in the final approach to the target, very low to avoid enemy's radar detection and to achieve the hit against the low ships profile.

The height above the sea depends also on the sea level.
The effect of the altimeters errors, sea motion and guidance law is a slow variation of the altitude of the missile

around the designed medium level. A medium height of 2 meters above the sea with fluctuation of 0.5 meters and a period of 2 seconds was considered.

2.1.2. Homing Guidance Law.

The guidance law is a proportional navigation that produce a rate of change of the missile trajectory (Ψ) which is k times the rate of change of the sight line (θ). K is called navigation constant, e.g.:

$$\dot{\Psi} = K\dot{\theta}$$

Typical values of K is between 3 and 4. In the missile simulation we used the value of k = 3.

In Fig. 2.1.2.1. a picture of the missile and target references is shown in the horizontal plane.

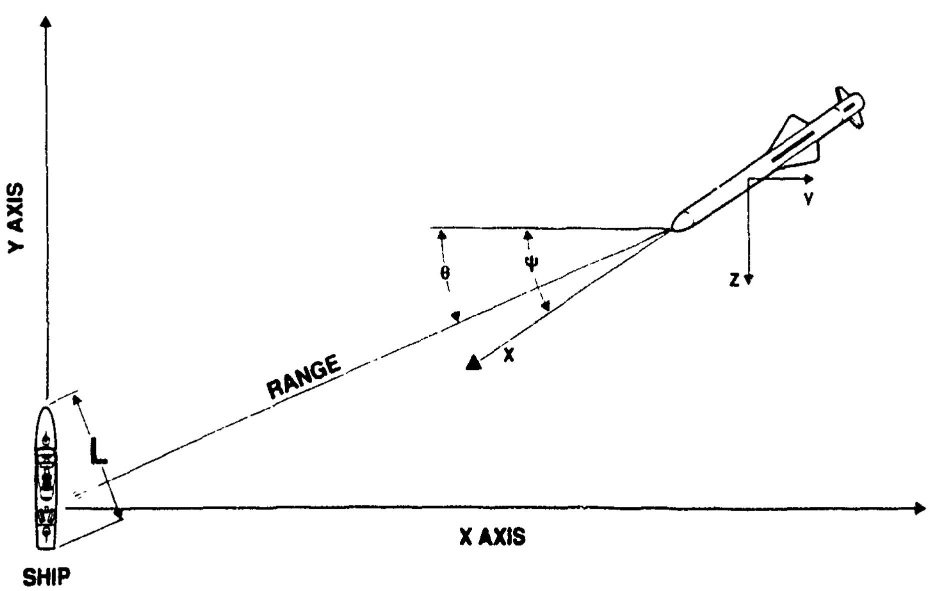


Fig. 2.1.2.1. - Modelling Reference System.

The value of the angle of sight θ is measured by the homing radar and its rate is calculated by the seeker.

2.1.3. Seeker Transfer Function.

The seeker represents the homing radar and the homing head that computes the angular rate of change of the sight line. Internal radar errors and noise errors are not considered since theirs effect on missile guidance is negligible with respect to the glint noise effect.
The derivative of the line of sight angle is calculated by a filter with the following transfer function.

$$G(s) = \frac{S}{Ts\,S + 1}$$

where Ts is the time constant of the Seeker.

2.2. GLINT NOISE MODEL.

The radar echo received from the missile is the form combination of a great number of scattered echoes along the ship. Because of the target and missile motion, the phase and the amplitude of each echo from the scatterers vary and so the global echo and the apparent center of the target change.
A frequency analysis of the time records of the glint from some ship targets and complex electromagnetic models of ships showed that the glint noise spectrum may be approximate with a noise passed through a first order filter lag of time constant TG.

The amplitude (mean square value) of the glint may vary considerably with the target aspect and from target to target. A good estimate of glint noise amplitude is given by the following formula:

$$\sigma^2_{glint} = \frac{L^2}{24\,R^2}$$

where:

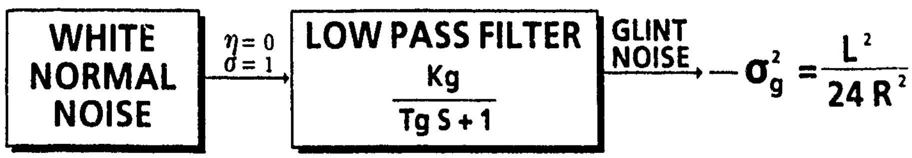
σ^2_{glint} means square value of glint

L effective radar target width (Fig. 2.1.2.1.)

R range from target to missile

The noise spectrum of the glint is generally not stationary but it changes by relative radar-target angular rate and target aspect.
For the purpose of this study the noise spectrum has been considered constant corresponding to fixed sea state and not target evasive manoeuvre.

In Fig. 2.2.1. the glint noise simulation scheme is shown:



where:

L = Effective Radar Target Length

R = Ship - missile Range

$$K_g = \sqrt{\frac{T_g}{12\,\Delta T}}\; L/R$$

ΔT = Simulation Sampling Period

Fig. 2.2.1. - Glint Noise Model.

The desidered final mean square value, as a function of L, R, Tg is obtained by setting:

$$K_g = \frac{L}{R} \cdot \sqrt{\frac{T_g}{12\,DT}}$$

DT is the sampling period of the numerical simulation.

2.3. MISSILE TRAJECTORY GENERATION MODEL.

The missile trajectory are obtained as the combination of the previous models added with the necessary parts to complete the simulation as coordinate transformation, time integration, etc.
Fig. 2.3.1. shows the block diagram of the complete model in the horizontal plane.

From the missile and target position, the true line of sight angle is computed in the absolute reference plane Oxy (Fig. 2.1.2.1.). The glint noise is added to the true angle of sight and the seeker calculates the derivative of this angle. The autopilot computes the lateral acceleration to obtain the derivative of the missile trajectory that is k times the rate of change of the line of sight. The value of the controlled lateral acceleration is $K \cdot V \cdot \theta$ where V is the missile speed.
The lateral acceleration in the missile body axes is then transformed into the absolute reference to have the missile motion by time integration.

Examples of trajectories are shown in Fig. 2.3.2. with and without glint noise against a fixed target with effective length of 50 m.

The Figure shows the effect of glint noise on the missile motion. An example of lateral acceleration due to glint noise is shown in Fig. 2.3.3.

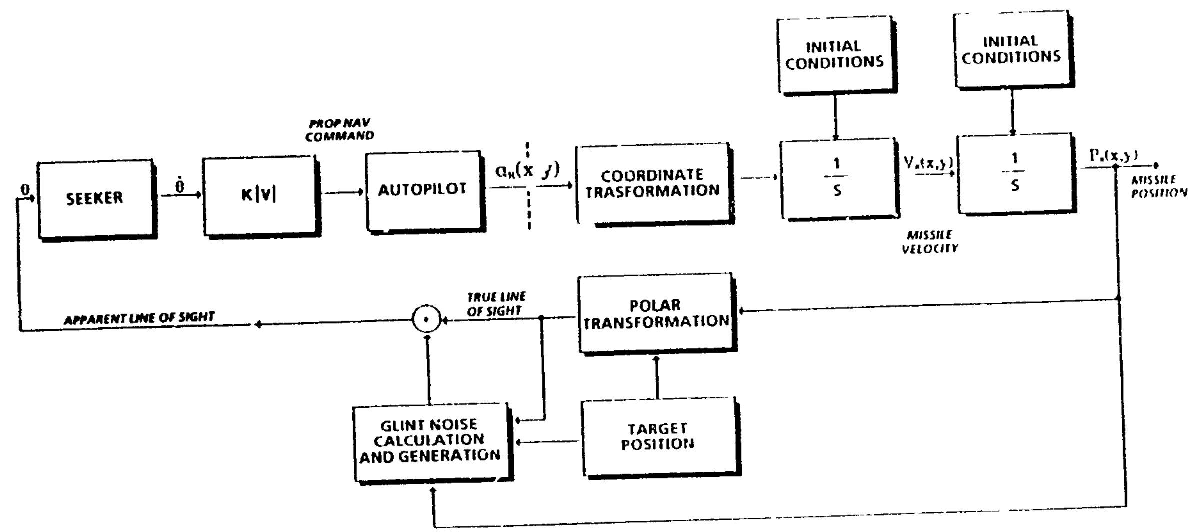


Fig. 2 3.1. - Missile Trajectory Generation Model.

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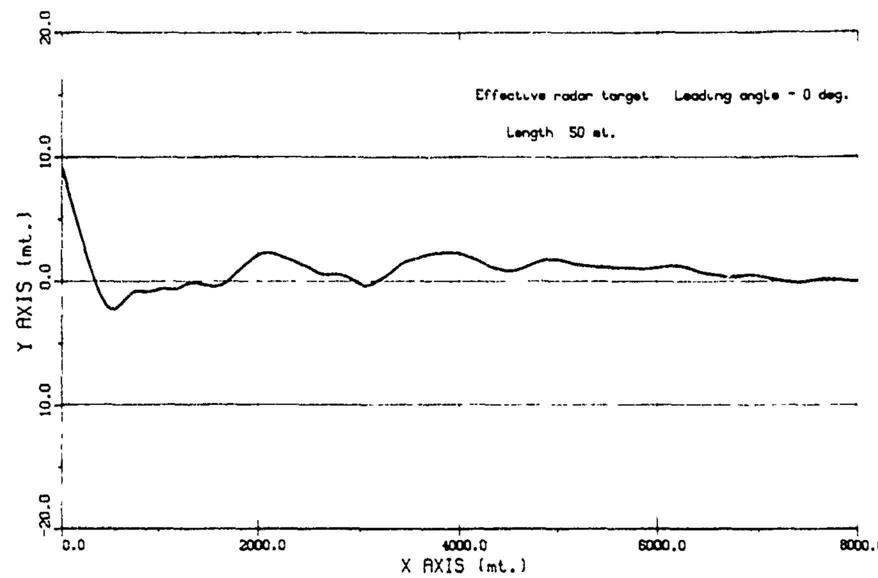


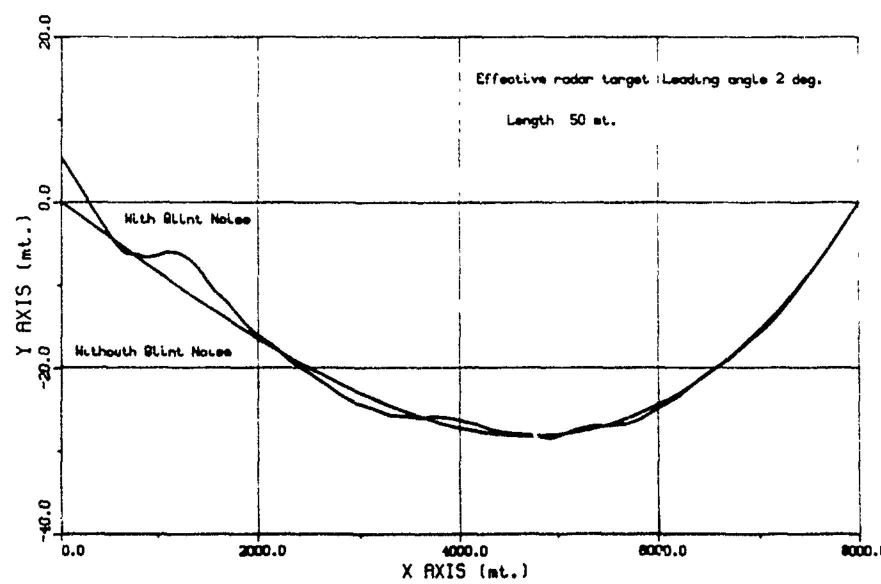
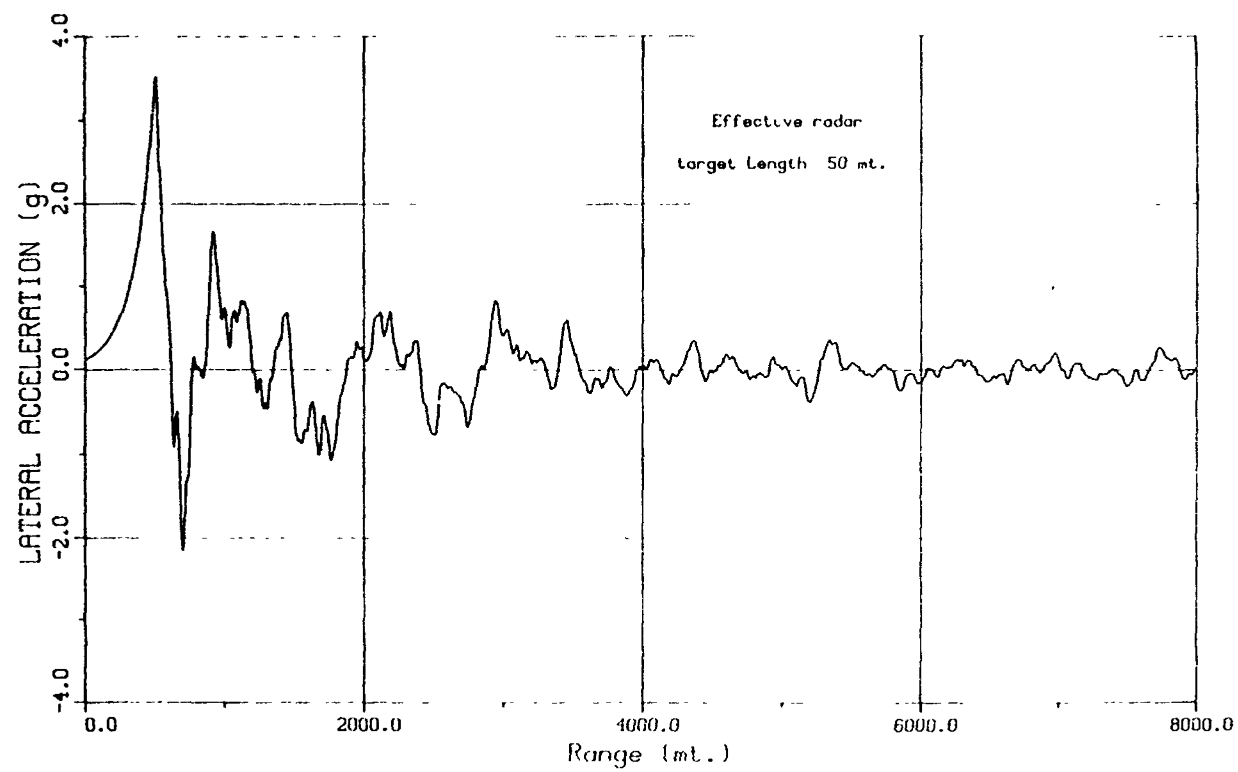


Fig. 2.3.2. - Example of Attack Trajectories.


Effective radar
target Length 50 mt.
LATERAL ACCELERATION (g)
4.0
2.0
0.0
-2.0
-4.0
0.0
2000.0
4000.0
6000.0
8000.0
Range (mt.)

33.12

3. MISSILE TRAJECTORY MODEL RESULTS.

With the model of Fig. 2.3.1. several attack trajectory of a sea skimming missile has been obtained, in presence of glint noise, against different target size as follow:

Target type A	10 meters
Target type B	25 meters
Target type C	50 meters
Target type D	80 meters

These values represent the effective length of the small ships considering the real size and angles of attack between 0 and 90 degrees with respect to the main ship axes.
To simplify the analysis of the results, the target is steady in the origin of the reference axis and the missile is steered on its beam. The initial homing phase of the missile is 8 km from the ship.

Fig. 3.1. shows the RMS value of the missile lateral displacement with respect to the theoretical straigth trajectory as a function of range. The medium value of the displacement is very close to zero.

Fig. 3.2. shows the spectral power density of the lateral displacement.

The results show that as the glint noise increases, with the inverse of range and with the target size, the lateral motion of the missile increases producing a random, and not predictable deviations around the medium trajectory.
The missile lateral motion can be modelled as a colored random noise with amplitude function of the range and of the target size. The transfer function of the autopilot and the proportional navigation law cut down the band, and the principal lateral motion is limited to 0.1 Hz.

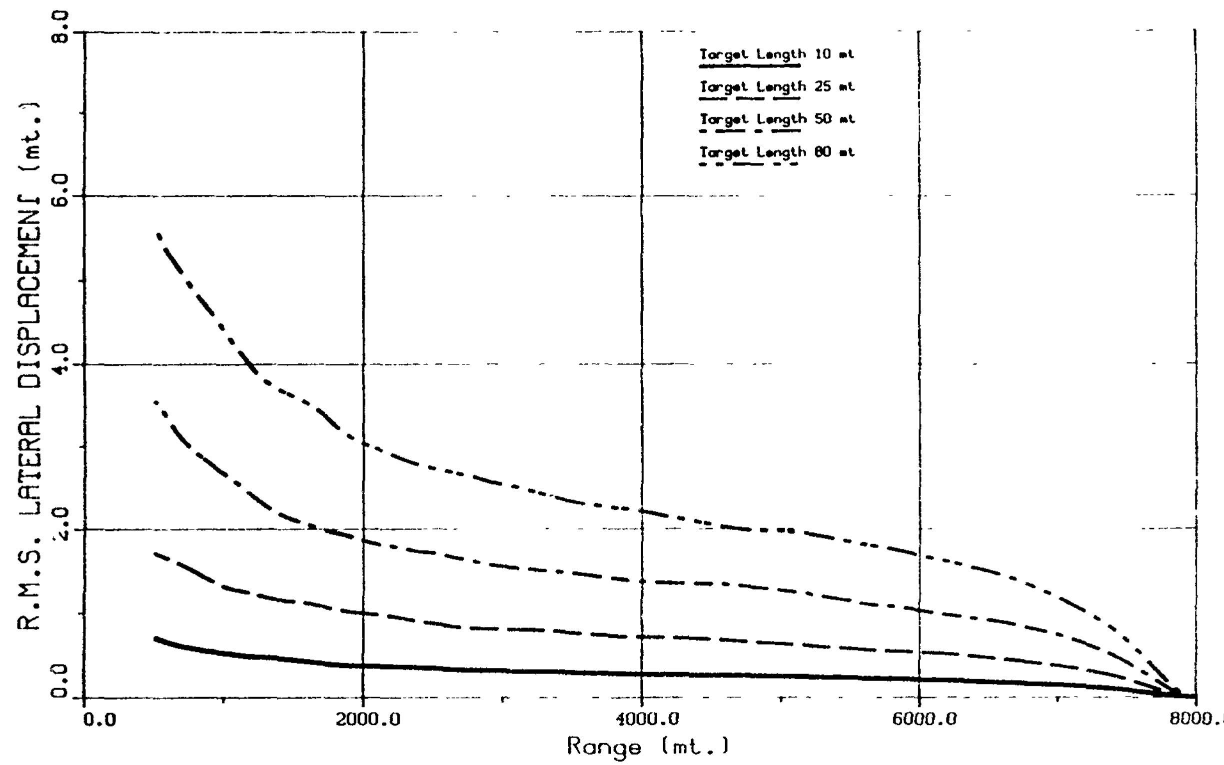


Fig. 3.1. - Modelling Results RMS Missile Lateral Displacement.

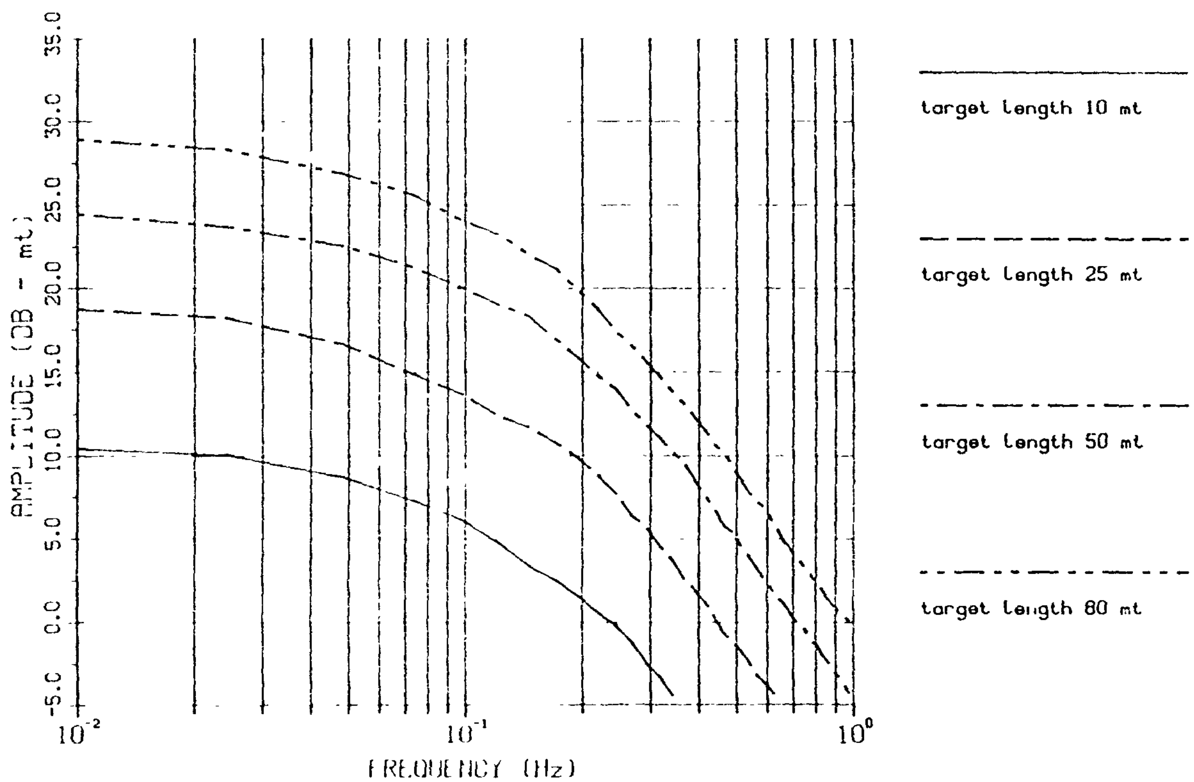


Fig 3.2 - Lateral Displacement Spectrum

33.15

4. INFLUENCE OF MISSILE LATERAL MOTION ON CIWS PERFORMANCE.

4.1. INTRODUCTION.

A gun based defence system estimates the missile trajectory parameters to predict the future impact point. This is done by the estimation of the actual point, the kinematic parameters of the missile and the prediction of the missile position at the expected instant of shell impact.

If the missile flies straight, the errors in the estimate of the impact point are only due to the sensors measurement errors.

If the missile manoeuvres around a nearly straight trajectory, a non zero lateral velocity generates an excessive expected lateral motion of the missile, proportional to the prediction time, (time of flight of the shell) on the impact point predictor.

In the reality the missile moves oscillating around a smoothed line with impredictable random manoeuvres.

The performance of a gun based close in system (CIWS), which aim is to hit and detonate the missile warhead, is strongly influenced by the lateral missile motion due to the glint phenomena.

4.2. CIWS MODEL.

To investigate the influence of the missile movements on the CIWS performance, typical CIWS data have been inserted in an existing ship defence weapon system model (SHIPDEF). The computer model includes the missile trajectory model de-

scribed in Chapter 2.3. and simulates the whole defence system engagement as:

- target tracking;
- target data smooting and evaluation of target kinematic data;
- computation of gun aiming point;
- ship motion stabilization and gun aiming;
- firing action.

The results is the probability of hit the missile computed through a Montecarlo statistic method.

The data utilized to characterize the CIWS were:

- Muzzle velocity	1400 m/s
- Rate of fire	5000 r/min
- Global dispersion	2 mrad (1 sigma)
- Burst duration	2 sec
- Type of shell	direct impact
- First intercept range	800 m
- Last intercept range	300 m
- Tracking filter	2 states
- Sensor accuracy	0.7 mrad (1 sigma)

4.3. ENGAGEMENT SCENARIO.

The engagement range for the CIWS was selected between 800 and 300 meters where, due to the short time of flight and the short engagement range, the effectiveness of the weapon is the maximum possible; engagement at range less than 300 m was not considered useful because the residual time of flight of the missile is less than 1 sec a d also the warhead detonation does not avoid the ship damaging.

The missile warhead section, used to compute the hit probability, was considered of 0.2 m radius.

4.4. CIWS PERFORMANCE.

The CIWS performance is shown in the figures from 4.4.1 to 4.4.3.

The figures show the cumulative hit probability of the CIWS as a function of the impact range and effective radar target length.

The hit probability has been computed for the case of at least one, two or three hits.

4.5. REMARKS ON CIWS PERFORMANCE.

To blast the missile warhead one or, probably, more hits are necessary depending on the missile warhead and the ammunition characteristics.

The results show how the missile natural manoeuvres due to glint noise drastically reduce the CIWS performance.

Fig. 4.5.1. summarizes the cumulative hit probability at 300 m (last impact range) as a function of the effective radar target length.

The performance degradation is mainly due to the impredictable random manoeuvres generated by glint effect and marginally influenced by the sensor accuracy.

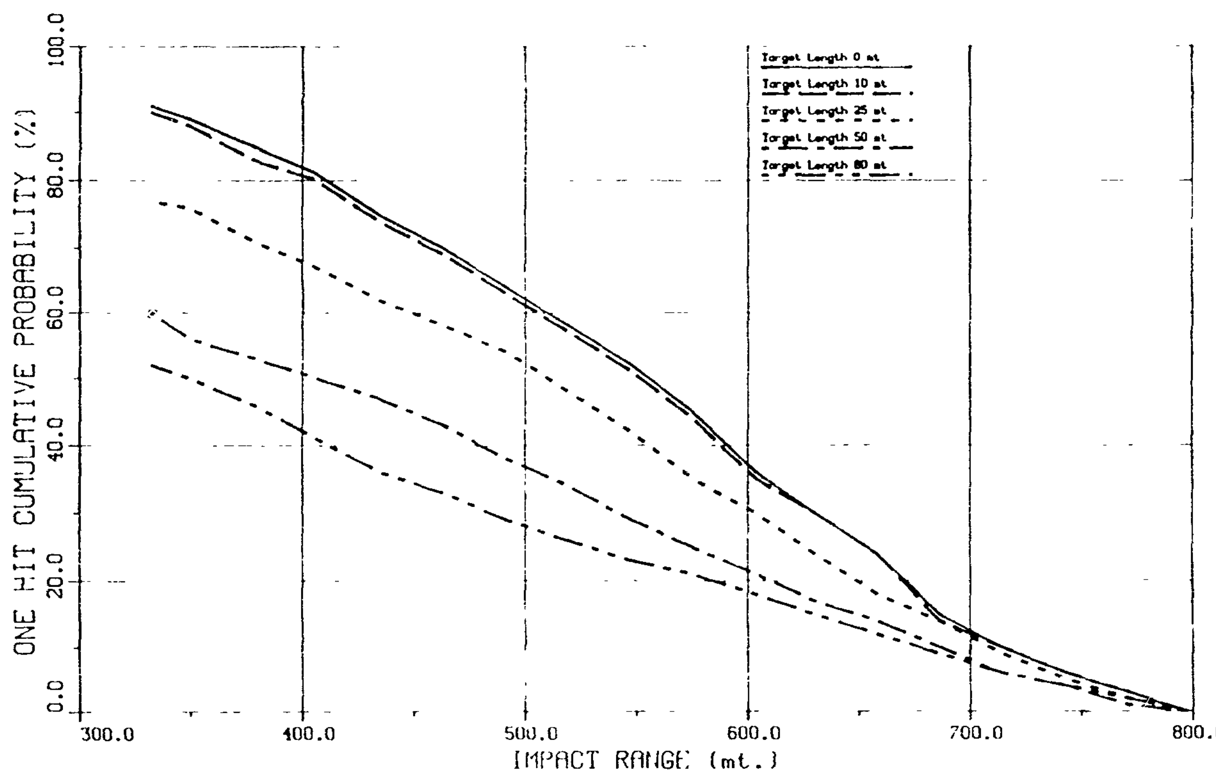


Fig 4 4 1. - CIWS Modelling Results.

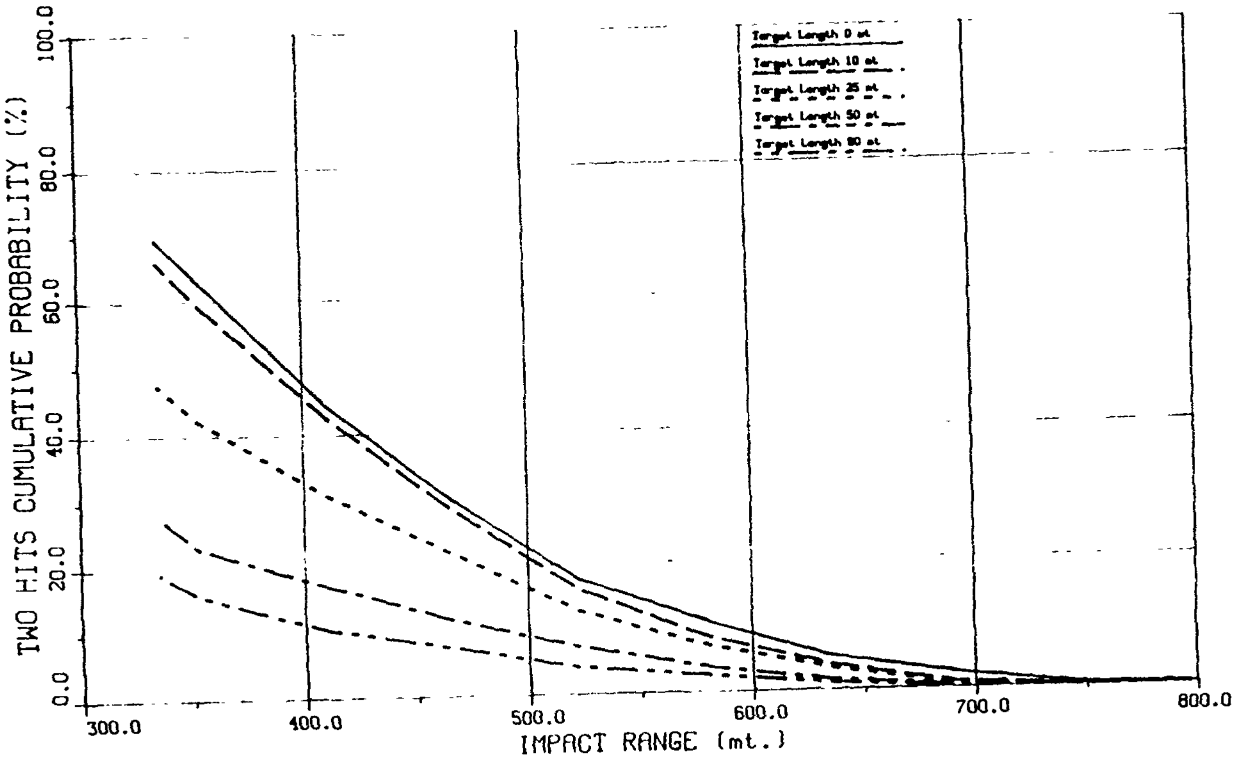


Fig. 4.4.2. - CIWS Modelling Results.

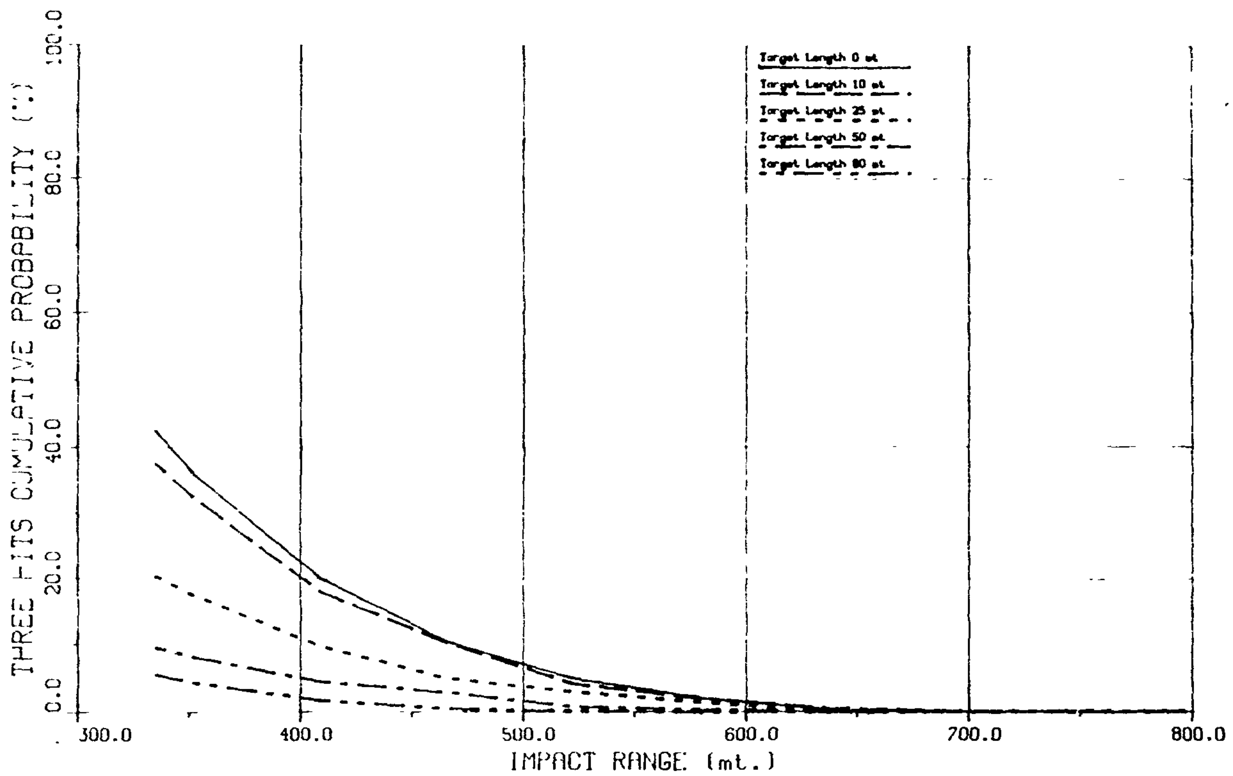


Fig. 4.4.3. - CIWS Modelling Results.

33.21

Figure 4.5.2. shows how the use of an ideal tracking sensor and optimized predictor algorithms does not improve signifi-catively the CIWS performance.

On the basis of the previous results, it is suggested that under an attack the bow of the ship be beared towards the threat approach direction; this will partially avoid the CIWS performance degradation and reduce the missile probability to hit the ship.

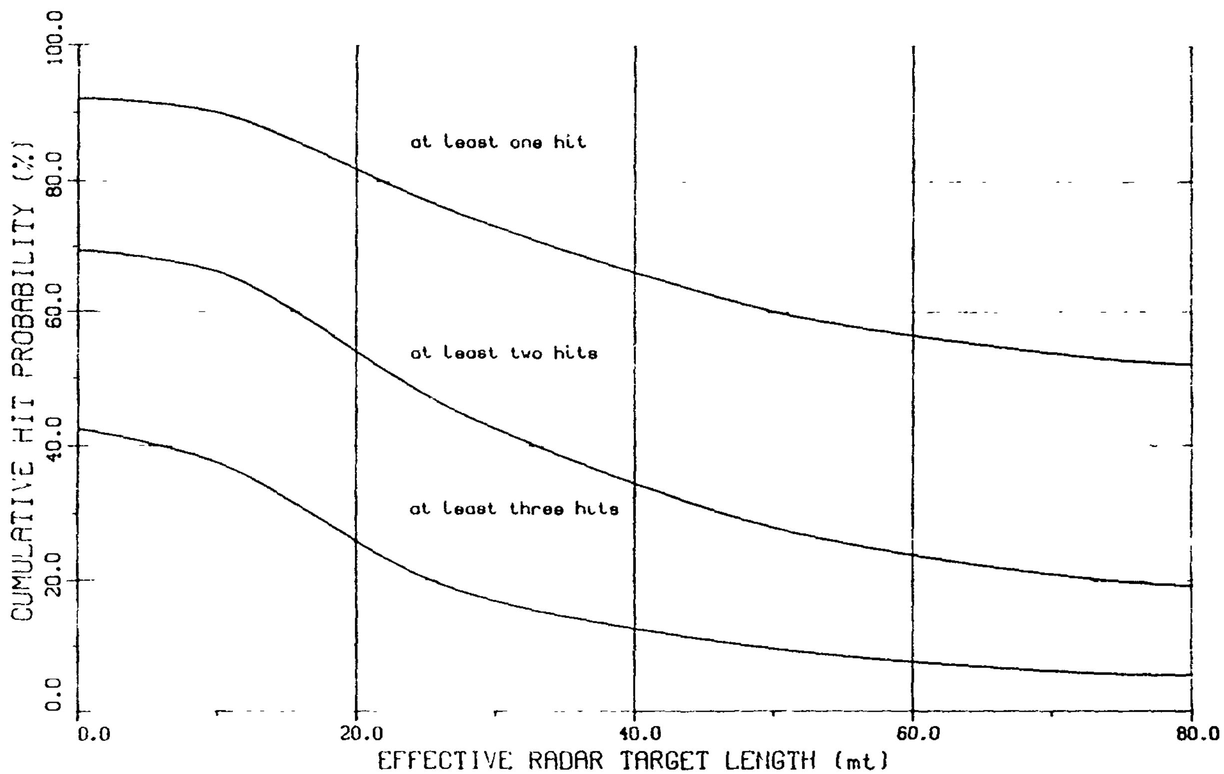


Fig. 4.5.1 - *CIWS Modelling Results.*

33.23

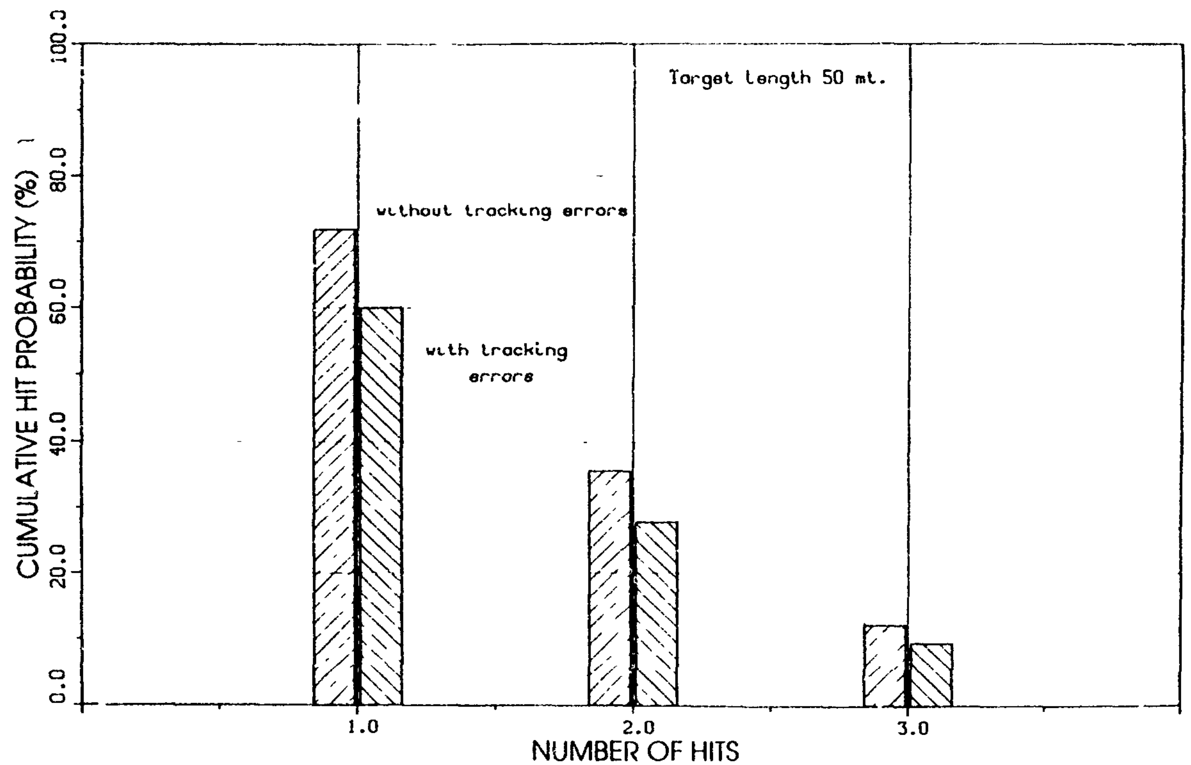


Fig 4.5 2. - CIWS Modelling Results.

5. EFFECT OF INTENTIONAL DISTURBANCES ON MISSILE TRAJECTORY AND CIWS PERFORMANCE.

A ship under attack can generate disturbances on missile seeker to reduce its hit probability.

Considering, as example, chaff disturbances, they can be utilized as follow:

CHAFF DECOY: when the chaff is launched during the missile acquisition phase it can deceive the missile seeker producing a false target.

CHAFF CLOUD: when the chaff is launched during the missile homing phase it can alter the missile seeker estimation of the ship angle of sight.

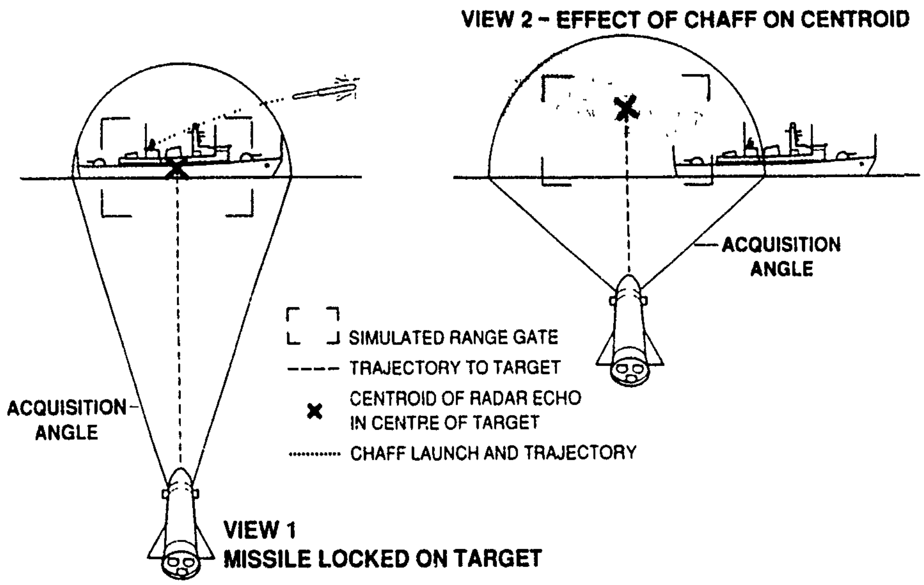
Fig. 5.1. shows examples of chaff utilization.

5.1. INFLUENCE OF CHAFF CLOUD ON MISSILE TRAJECTORY.

A chaff cloud, launched when the missile is in the homing phase can disturb the missile seeker, increasing the glint noise and creating a new apparent radar target center.

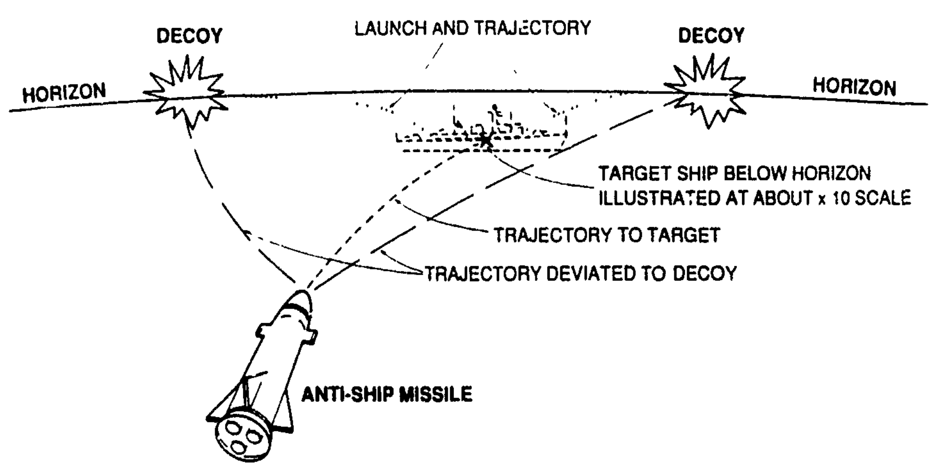
Normally, the chaff cloud is launched close to the ship, to allow its detection from the missile seeker, which is "range" locked on the target and then the ship goes away from the chaff.

Fig. 5.1.1. shows the effect of chaff cloud disturbance on missile trajectory for chaff launch when the missile is at 2 and 4 km from the ship.



Example of Chaff Clouds Utilization.

DISTRACTION MODE OF OPERATION - MISSILE VIEW



Example of Decoy Utilization.

Figure 5.1.

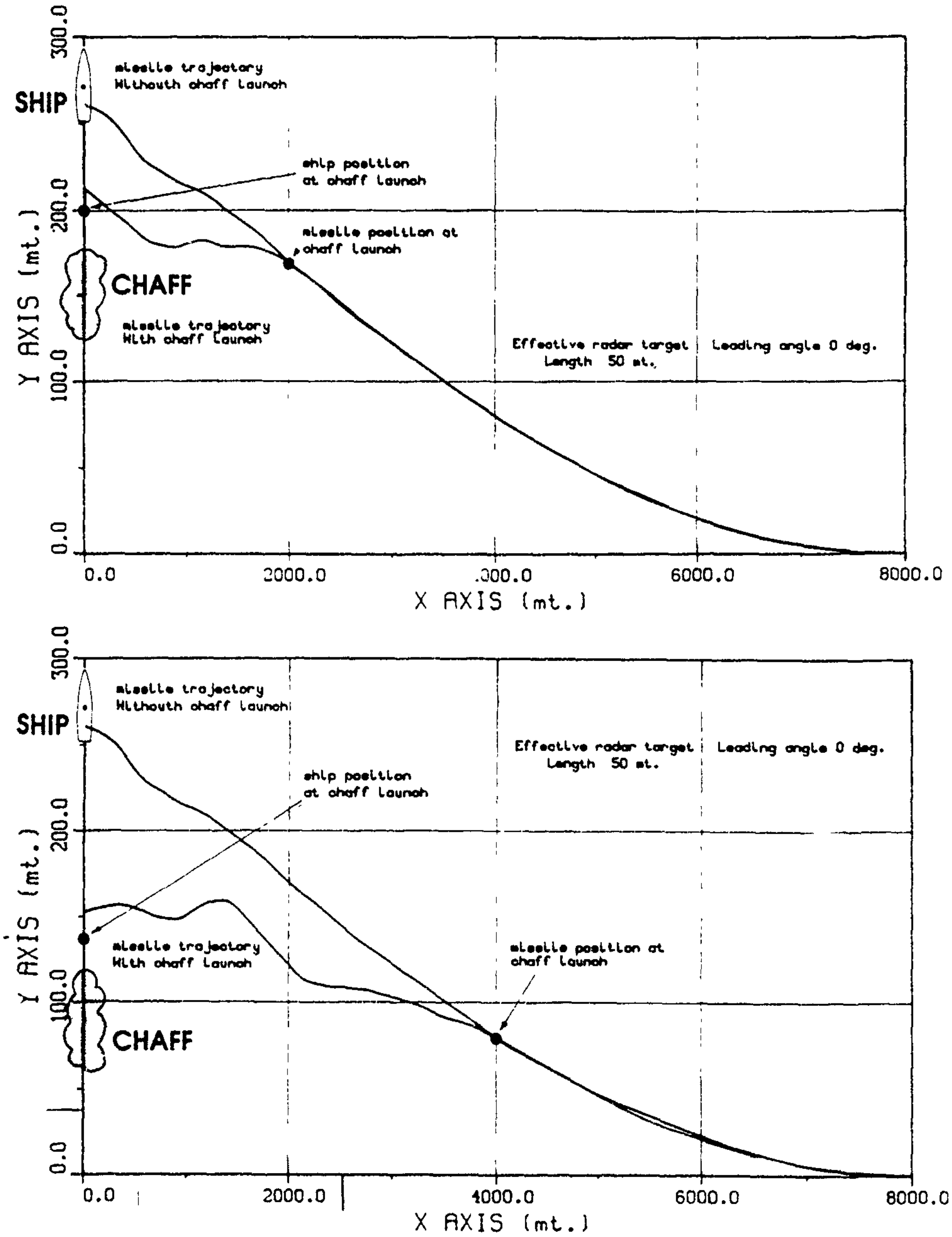


Fig. 5.1.1. - Chaff Cloud - Exampie of Attack Trajectories.

The ship is moving along the y - axis at the speed of 19 mph. The chaff cloud is launched behind the ship at short distance in order to remain within the missile seeker range gate and beam.

Fig. 5.1.1. shows that the effect of chaff launch increases if it occours when the missile is far enough from the ship.

The chaff cloud, as glint effect, induces additional missile lateral manoeuvres; Fig. 5.1.2. shows the missile lateral displacement (RMS values) in presence of chaff launch compared with the glint of the target only.

5.2. EFFECTS OF CHAFF CLOUD ON CIWS PERFORMANCE.

The increase of missile lateral manoeuvres due to chaff use produces, as secondary effect, a further reduction of the CIWS performance.

Considering the example of a 50 m target length and a chaff launch at the range of 4 km, the CIWS hit probability is shown in Fig. 5.2.1. compared with the case of glint only.

5.3. POSSIBLE COORDINATION IN THE UTILIZATION OF CIWS AND INTENTIONAL DISTURBANCES.

The results of the study have shown how the CIWS performance depends on the entity of missile natural manoeuvres in the final phase of the attack.

Because of the entity of missile manoeuvres is relate to the glint noise amplitude (and thus to the ship size seen by

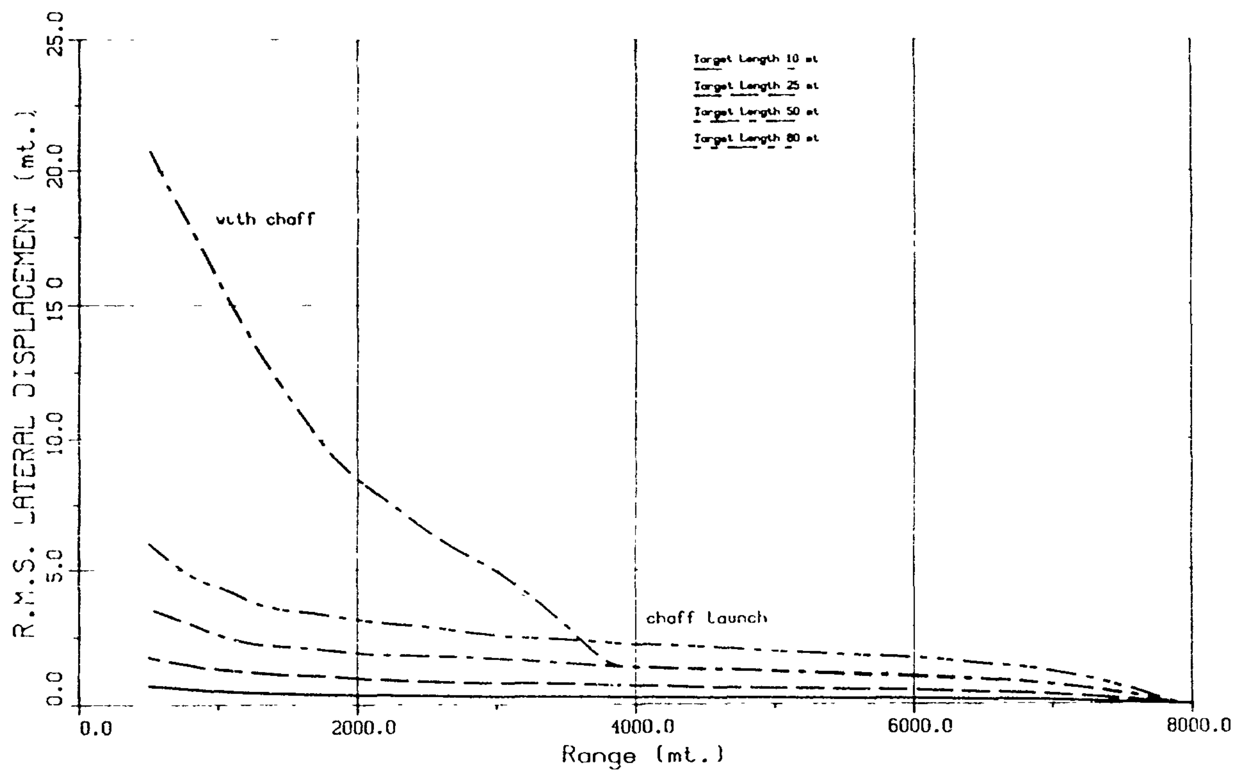


Fig 5 1 2 - Modelling Results RMS Missile Lateral Displacement

33.29

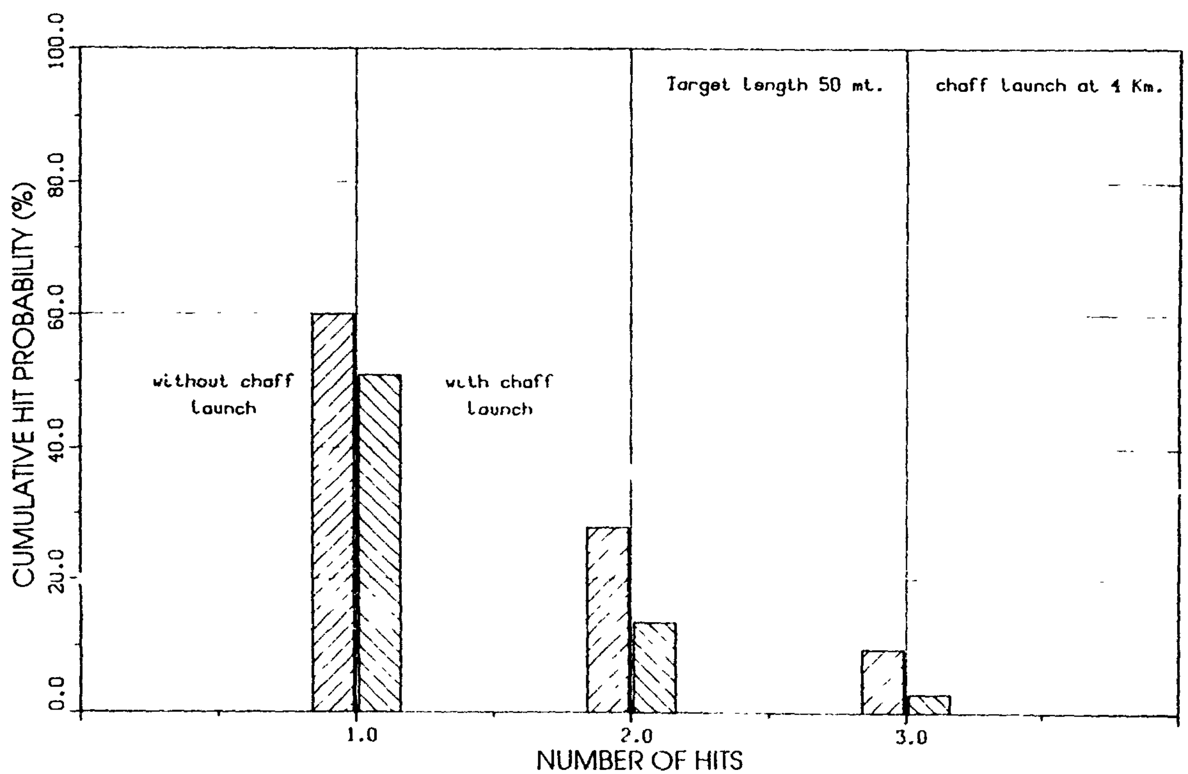


Fig 5 2 1. - CIWS Modelling Results Chaff Launch.

33.30

missile seeker) and to the use of chaffs, coordination in the use of CIWS, intentional disturbances and navigation control is useful to maximize the ship survivability.

Considering that every tactical consideration have to be related to the knowledge of the performance of the active and passive defence system on board ship, possible indication about the coordination of passive and active defence system can be done.

On the hypothesis that the chaff and missile behaviour reflects the results of this study, possible coordination can be as follow:

- Missile detection at medium range (8-15 km)
  (before homing phase)

  Utilization of:

  - Chaff decoys to deceive the missile
  - Long/medium range weapon system (if available).
  - Orientation of ship prow toward the missile approach direction to decrease missile hit probability and to increase CIWS effectiveness.
  - Use of CIWS

- Missile detection at short range (3-8 km)
  (during homing phase)

  If the missile approaches

  - near ahead: only CIWS utilization
  - abeam: utilization of chaff and CIWS

6. CONCLUSIONS.

A set of computer models has been realized to investigate the sea skimmimg missile natural manoeuvres in the final part of its attack trajectory.

Simplified model of glint induced by the ship target on missile seeker has been realized and inserted in the missile guidance model.

Results have shown the increase of the missile lateral manoeuvres, proportional to the target dimension and to the decrease of the missile distance.

Experimental results of sea skimming missile trajectories confirmed the results of the models.

A model of a representative Close In Weapon System (CIWS) has been used to compute the hit probability in various engagement conditions.

Results have shown that the probability of hit is generally not very high and the glint effect produces further reductions.

Intentional disturbances on missile seeker created on board ship produce effect similar to the glint noise on missile trajectory.

Simplified model of chaff cloud decoy has been realized to investigate its influence on the missile manoeuvres; results have shown an additional increase of the missile lateral displacements and then the reduction of CIWS hit probability when used together with chaff.

The probability of chaff to deceive the missile has not been investigated in this study and then the increase of ship survivability when using combination of intentional disturbances and CIWS has not been determined; neverthless a cocrdination of the defence systems is necessary to maximize the defence capability of the ship.

The knowledge of the expected performance of CIWS and intentional disturbances in the various engagement conditions keeps in the selection of the more effective solution for the defence action.

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